CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AMIR AINULARIFF BIN MAHMUD

ABSTRACT

This project focused on Fracture Toughness (FT) and Fatigue Crack Growth (FCG) tests of Compact Tension (C(T)) specimens to be performed using Amsler Universal Testing Machine. This project's main objective was to implement Crack Opening Displacement (COD) and compliance methods for crack measurements during FCG tests. This project used C(T) specimens for all tests. In order to setup this test, several accessories were fabricated, such as test specimens, clevis, integral knife edges, and gage beam. The test specimens, clevis, integral knife edges and gage beam fabrication were done at UTP's Manufacturing Lab using conventional lathe and milling machines, electric discharge machining wire cut and other manufacturing tools and methods. The actual tests were conducted in UTP's Materials Lab**.** Before the FCG tests were run, several FT tests were done using aluminum and steel specimens in order to improve the previously-run FT tests and also to prepare the machine's accessories for the assembly and conduct of subsequent tests. Lastly, FCG tests were performed successfully, and the procedures for this test were prepared.

ACKNOWLEDGEMENT

The author would like to acknowledge Dr. Azmi Bin Abdul Wahab as the project supervisor and all of Department of Mechanical Engineering (Manufacturing and Materials Lab), Universiti Teknologi PETRONAS for their help in the use of Amsler Universal Testing Machine and Conventional Lathe Machine and support in completing the project. Thanks to the FYP examiners especially Dr. Mokhtar Bin Awang, Ir. Hj. Idris Bin Ibrahim and Dr. Khairul Fuad Bin Muhammad Rasyid from the Department of Mechanical Engineering for their commitment to be the examiners during the seminars and oral presentations.

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ABBREVIATIONS AND NOMENCLATURES

ASTM	American Standard for Testing and Materials
C(T)	Compact Tension
COD	Crack Opening Displacement
EDM	Electrical Discharge Machine
FCG	Fatigue Crack Growth
FT	Fracture Toughness
FYP	Final Year Project
UTM	Universal Testing Machine

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Crack growth can be caused by cyclic loading, a behavior called as Fatigue Crack Growth (FCG). A metal subjected to a repetitive or fluctuating stress will fail at a stress much lower than that required to cause fracture on a single application of load. Failures occurring under conditions of dynamic loading are called fatigue failures, presumably because it is generally observed that these failures occur only after a considerable period of service. Cracks can occur naturally in engineered components due to the combination of environmental effects, material and geometric properties.

1.2 PROBLEM STATEMENT

Currently UTP's Material Lab does not have an automated method to measure crack length during FCG tests. This lab does not have sufficient accessories to perform FCG tests even though the Amsler Universal Testing Machine (UTM) is capable of performing the test. Thus, the procedure for the test will be prepared and all the required accessories will be fabricated.

1.3 Objectives

The main objective for this project is to implement Crack Opening Displacement (COD) and the compliance methods for crack length measurement during constant amplitude FCG test on compact tension (C(T)) specimens. In addition, previously-run Fracture Toughness (FT) tests and methods will be enhanced by improving the FT test configurations and accessories, which can also be used for the FCG tests. This project requires the set up of the UTM for FCG tests. All the required accessories such as test specimens, clevis, integral knife edges and gage beam will be fabricated. This project will run FCG tests on C(T) specimens of mild steel and aluminum. Last but not least is to produce a complete set of procedures to run the FCG test.

1.4 Scope of Study

This project will focus on FCG tests for C(T) specimen with a size of 70 mm × 70 mm × 9 mm. The testing process will require the use of two main equipment which are, Amsler UTM and Epsilon extensometer.

CHAPTER 2

LITERATURE REVIEW

2.1 FRACTURE TOUGHNESS

In materials science, Fracture Toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for virtually all design applications. It is denoted K_{Ic} and has the units of $\text{MPa}\sqrt{\text{m}}$ [1].

Fracture toughness is a quantitative way of expressing material's resistance to brittle fracture when a crack is present. If a material has a large value of fracture toughness, it will probably undergo ductile fracture. Brittle fracture is a characteristic of materials with a low fracture toughness value. In other word, fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw [2]. It is a very important material property since the occurrence of flaw is not completely avoidable in the processing, fabricating, or servicing of a material.

Flaws may appear as cracks, voids, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading condition and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture.

Fracture toughness can be determined using a parameter called stress intensity factor. It is a function of loading, crack size, and structural geometry. The stress intensity factor can be represented by the following equation,

$$K_I = \sigma\sqrt{\pi a \beta} \qquad (1)$$

Where σ is the applied stress in MPa, a is the crack length in meter, and β is the component geometry factor.

A Roman numeral subscript indicates the mode of fracture and all of the three modes of fracture can be seen in the Figure 2.1. Mode I fracture is the condition in which the crack plane is normal to the direction of largest tensile loading. This is the most commonly encountered mode and, therefore, for the remainder of the report, we will only consider K_I fracture mode.

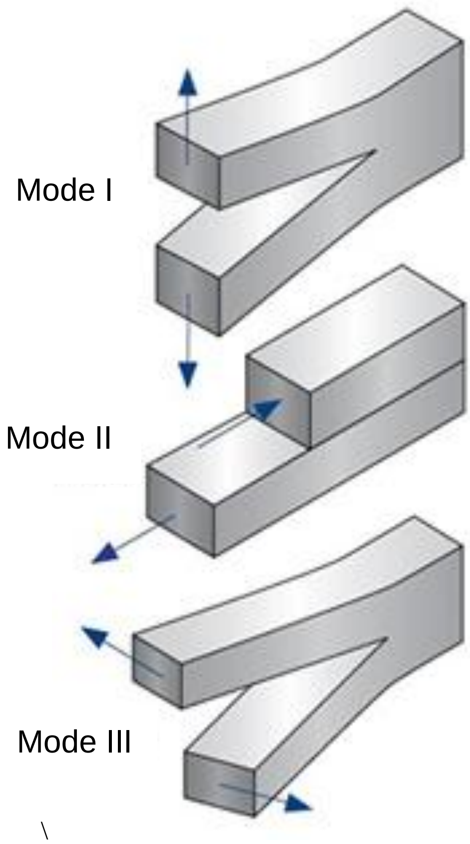

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Figure 2.1: Modes of fracture [2]

2.2 FATIGUE CRACK GROWTH

Consider a growing crack that increases its length by an amount Δa due to the application of a number of cycles ΔN. The rate of growth with cycles can be characterized by the ratio of Δa / ΔN or, for small interval, by the derivative da/dN. A value of fatigue crack growth rate, da/dN, is the slope at a point in a versus N curve as shown in Figure 2.2 [4].

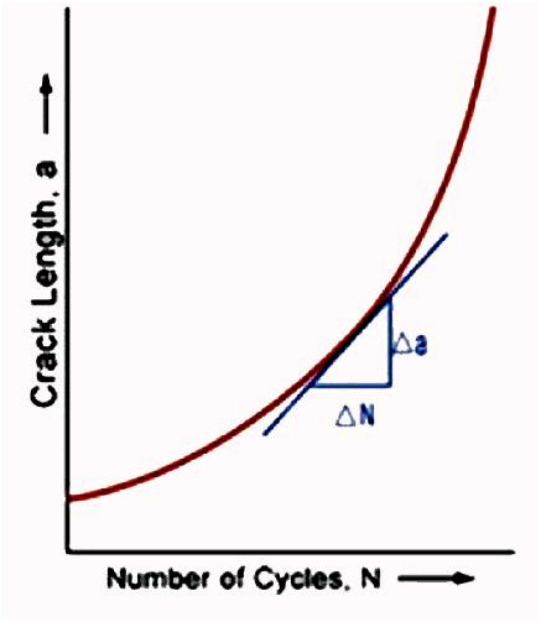


Figure 2.2: Graph of a, crack length versus N, number of cycles [3]

Fatigue crack growth in metals can be divided into three stages which are crack initiation, stable crack growth and unstable crack growth that will lead to the final fracture [5]. The first stage, crack initiation is a region where da/dN increases rapidly with the cyclical component ΔK of the Stress Intensity Factor K. Generally, second stage is the major interest since it represents the major portion of useful fatigue life in the engineering components.

Specifically, K can be defined as measure of the severity of a crack situation as affected by crack size, stress and geometry [4]. The crack growth can be defining using Paris Equation which is:

$$\frac{da}{dN} = C(\Delta K)^m \qquad (2)$$

Where a is the crack length, N is the cycles and m is constant typically in the range of 3 to 5 (for metals). Stress intensity factor range can be expressed as:

$$\Delta K = K_{max} - K_{min} \tag{3}$$

While K, can be calculated from this equation:

$$K = \sigma\sqrt{\pi a} \tag{4}$$

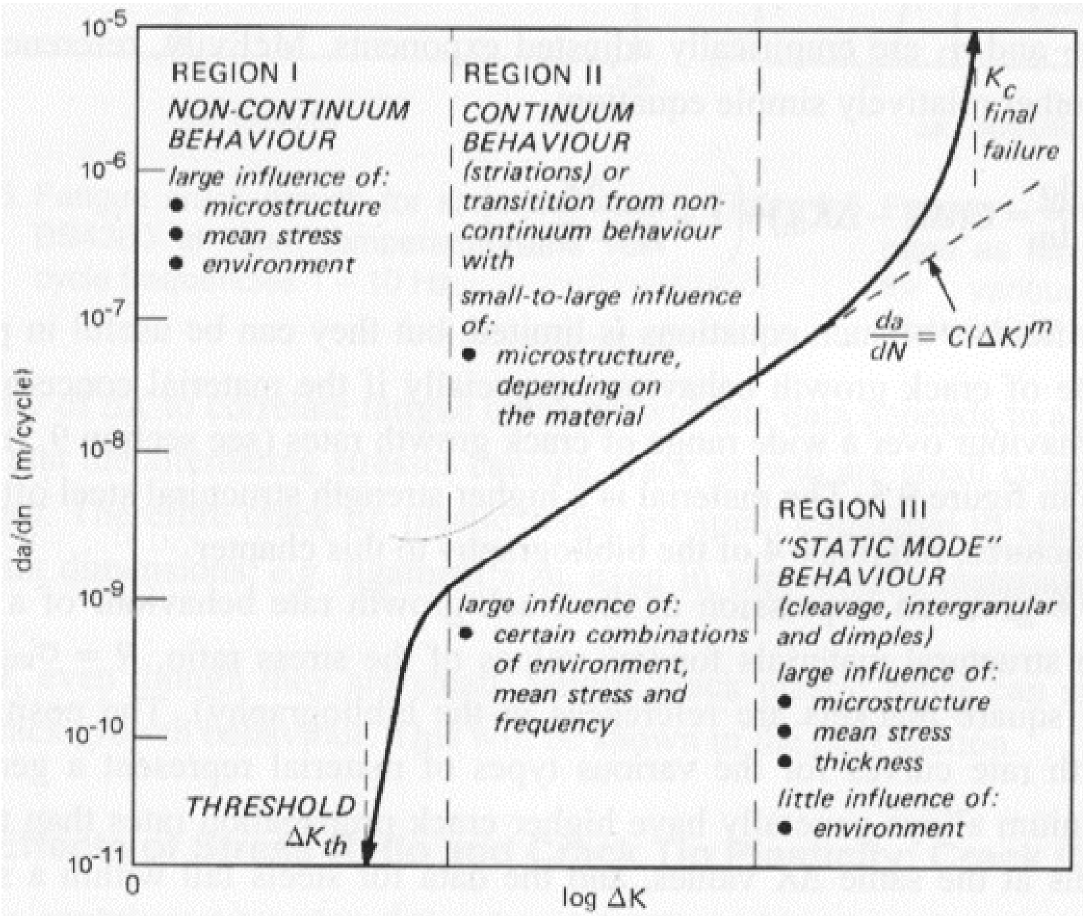


Figure 2.3: Paris Law Curve [6]

2.3 CRACK MEASUREMENT VIA CRACK OPENING DISPLACEMENT (COD)

The Crack Opening Displacement (COD) will measure the resistance of a material to the propagation of a crack. COD is used on materials that can show some plastic deformation before failure occurs causing the tip to stretch open. Accurate measurement of this displacement is one of the essentials of the test.

In order to prepare a specimen for a COD test, a notch is machined in the centre of the specimen and then an actual fatigue crack is carefully induced at the base of the notch. The crack must be long enough to pass through any area displaying plastic deformity caused by the machining process.

The crack opening is plotted against the load applied. There are three basic types of fracture behavior with this test: brittle fracture, pop-in, and ductile fracture. Referring to the Figure 2.4, the first curve shows a completely plastic or ductile behavior. The second curve shows a pop-in where the crack initiates in a brittle manner but is soon arrested by tougher more ductile material. This behavior can occur many times giving the curve a saw tooth appearance. And the third curve depicts a brittle fracture with little or no plastic deformation.

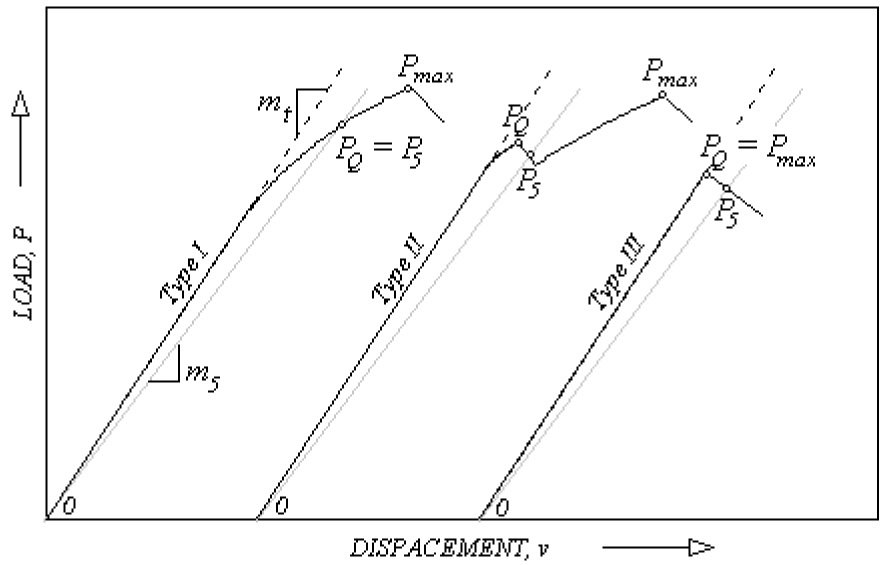


Figure 2.4: Principal Types of Load-Displacement Records [7]

2.4 ASTM E399

This test method, Plane-strain Fracture Toughness of Metallic Material covers the determination of the plane-strain fracture toughness (K_{Ic}) of metallic materials by tests using a variety of fatigue cracked specimen having a thickness of 1.6mm or greater [6].

2.4.1 Test Method

This test method can be divided into two major parts. The first part will give the general information concerning the recommendation and requirement for K_{Ic} testing. The second part is composed of annexes that give the displacement gage design, fatigue cracking procedures, and special requirement for the various specimen configurations covered by this method.

2.4.2 Test Purposes

This test method can serve the following purposes such as in research and development to establish, in quantitative terms, significant to service performance, the effects of metallurgical variables such as composition or heat treatment, or of fabricating operations such as welding or forming, on the fracture toughness of new or existing materials. In service evaluation, to establish the suitability of a material for a specific application for which the stress condition are prescribed and for which maximum flaw sizes can be established with confidence.

2.4.3 Design Standard

<u>Gage</u>

The gage consists of two cantilever beams which are clamped together with two nuts as shown in Figure 2.5 [7]. The material for the gage beams should have a high ratio of yield strength to elastic modulus. A detailed dimension for the beams is given in Figure 2.6. The recommended gage length is from 5.1 mm to 6.3 mm.

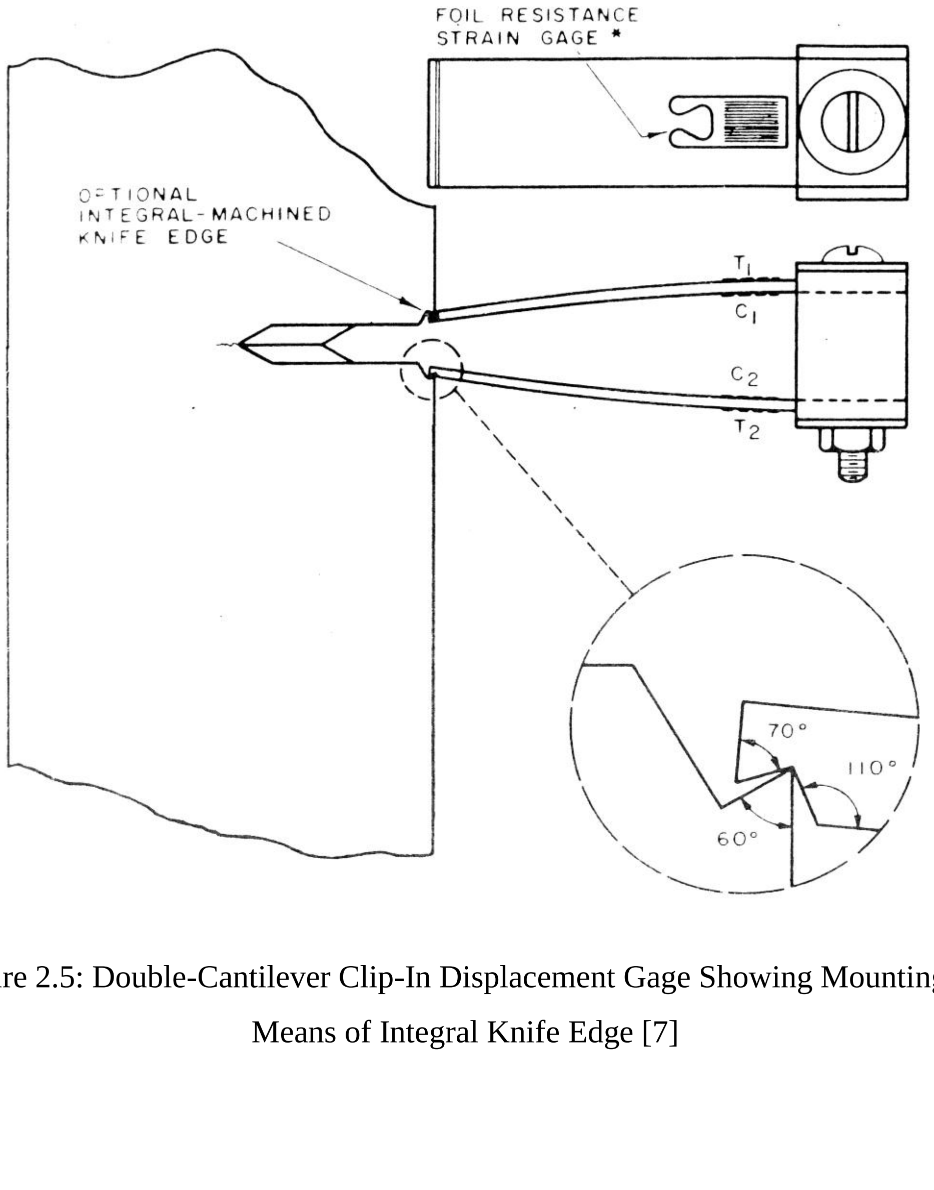


Figure 2.5: Double-Cantilever Clip-In Displacement Gage Showing Mounting by Means of Integral Knife Edge [7]

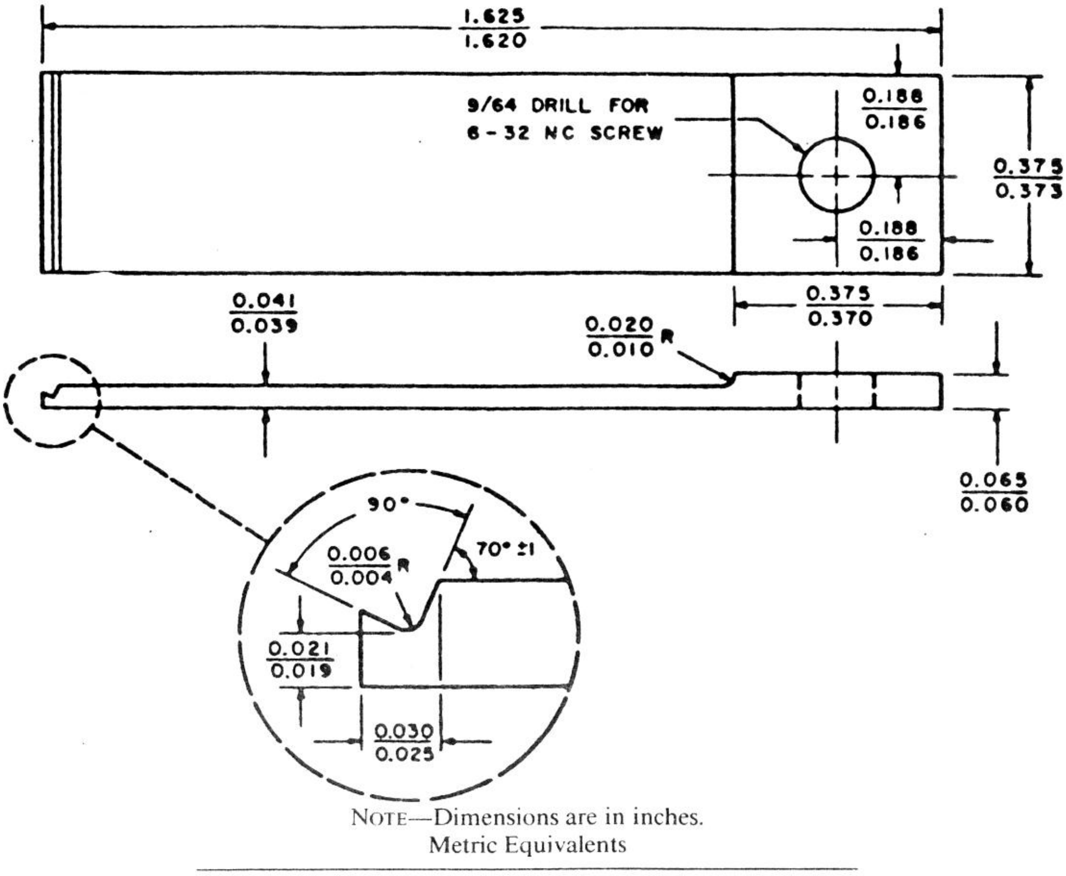


Figure 2.6: Beams for Double-Cantilever Displacement Gage [7]

Integral Knife Edges

A suggested design for the integral knife edge is shown below in Figure 2.7.

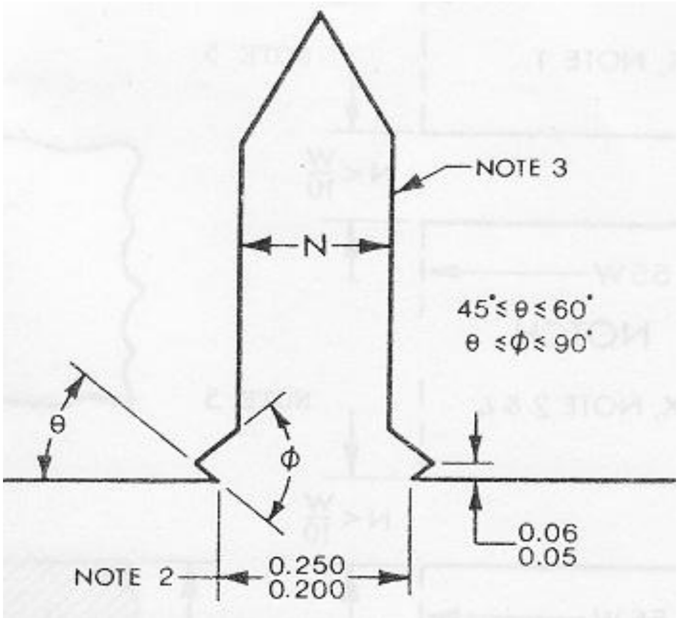


Figure 2.7: Example of Integral Knife Edge Design [7]

Compact Tension Specimen

Alternatively, the ratio of yield strength to Young Modulus can be used for selecting a specimen size that will be adequate for all the toughest material as shown in Table 2.1.

Table 2.1: The Ratio of Yield Strength to Young Modulus and Correspond Minimum Recommend Thickness and Crack Length [6]

σ_{ys} / E	Minimum Recommended Thickness and Crack Length (mm)
0.0050-0.0057	75
0.0057-0.0062	63
0.0062-0.0065	50
0.0065-0.0068	44
0.0068-0.0071	38
0.0071-0.0075	32
0.0075-0.0080	25
0.0080-0.0085	20
0.0085-0.0100	12.5
0.0100-greater	6.5

The crack length, a (crack starter notch plus fatigue crack) is nominally equal to the thickness, *B*, and is between 0.45 and 0.55 times the width, *W*. The ratio *W/B* is nominally equal to two. The crack length (total length of the crack starter configuration plus the fatigue crack) shall be between 0.45 and 0.55 *W* as shown in the Figure 2.8. For a straight-through crack starter terminating in a V-notch, the length of the fatigue crack on each surface of the specimen shall not be less than 2.5% of *W* or 1.3mm minimum. For the fatigue crack extensional from the stress raiser tipping the hole shall not be less than 0.5 *D* on both surfaces of the specimen, where *D* is the diameter of the hole, 1.3mm minimum.

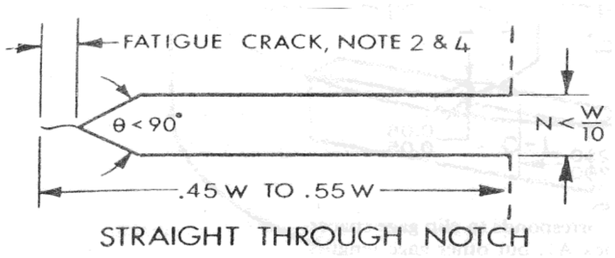


Figure 2.8: Crack Starter Notch and Fatigue Crack for Straight through Notch [7]

The standard compact tension specimen is a single edge notched and fatigue cracked plate loaded in tension. The configuration can is shown in Figure 2.9.

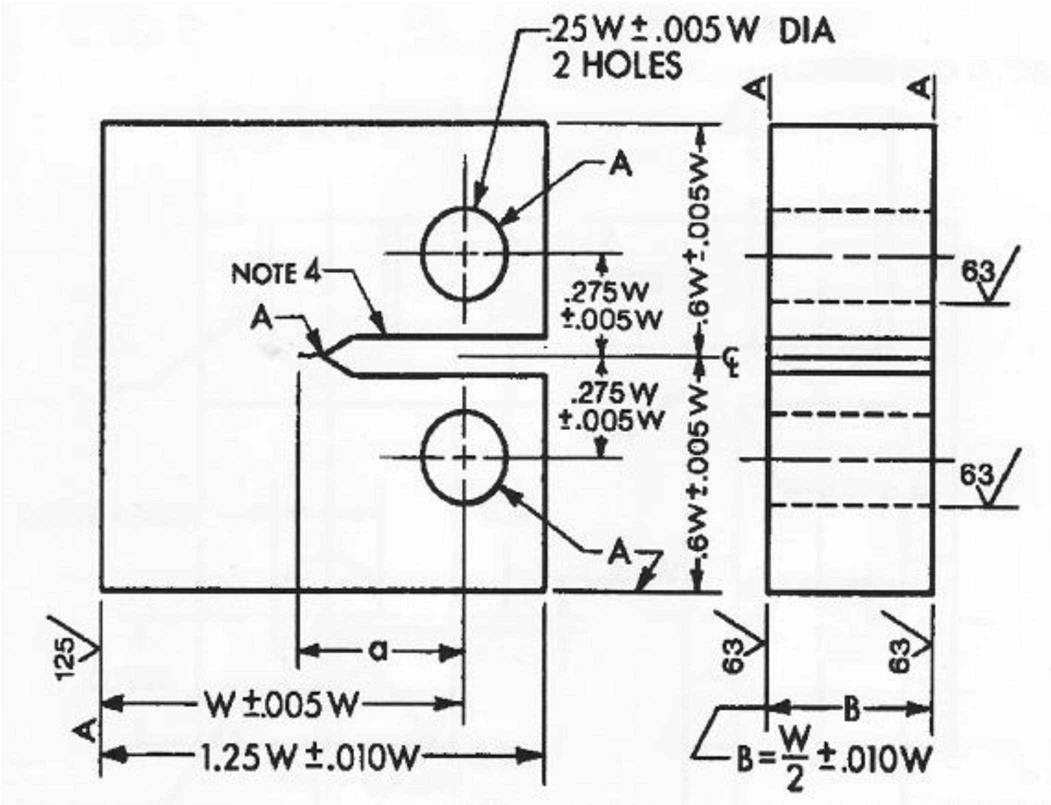


Figure 2.9: Compact Tension Specimen Standard Proportion and Tolerance [7]

<u>Testing Clevis</u>

A loading clevis suitable for testing arc-shaped specimen is shown in Figure 2.10. Both the ends of the specimen are held at the clevis and loaded with pins, in order to allow the rotation of the specimen during the test. Other design of clevis can be used as long as it can demonstrate that they will accomplish the same result as the design shown. Suggested dimension for the clevis and pins are having W/B = 2 for B > 12.7mm and W/B = 4 for $B \leq 12.7$mm.

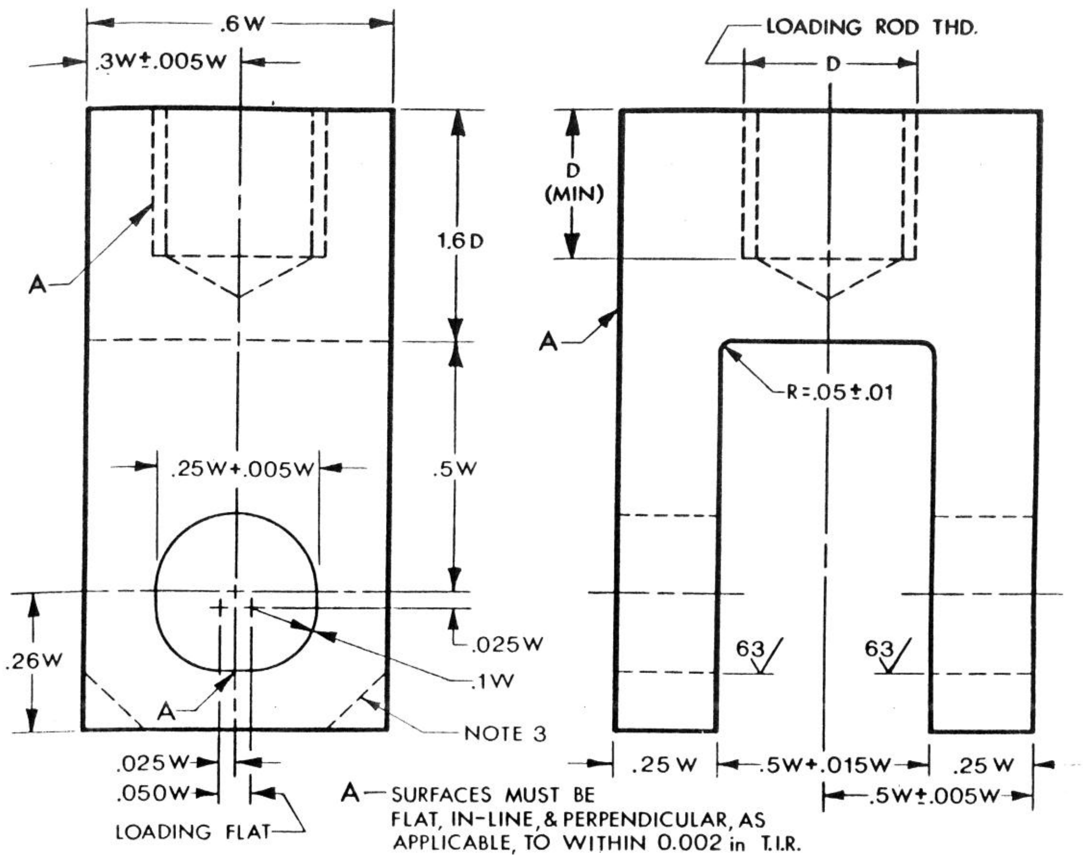


Figure 2.10: Tension Testing Clevis Design [7]

2.4.4 General Procedure

It is recommended that at least three replicate test to be performed for each material condition. There are three fundamental measurements for calculations of K_{Ic} are the thickness, B, the crack length, a, and the width, W. For conventional (static) testing load, the rate of increasing the stress intensity is within the range from 0.55 to 2.75 MPa-$m^{1/2}$/s. Make a test record consisting of an autographic plot of the output of the load sensing transducer versus the output of the displacement gage. The initial slope of the linear portion shall be between 0.7 and 1.5. It is conventional to plot the load along the vertical axis, as in ordinary tension test record.

2.5 ASTM E647

This standard is named as Standard Test Method for Measurement of Fatigue Crack Growth Rates. This test method covers the determination of constant-load-amplitude fatigue crack growth rate above 10^{-8} m/cycle, using either compact type or center-cracked-tension specimens. Results are expressed in terms of the crack-tip stress intensity range, defined by the theory of linear elasticity [8].

2.5.1 Significance and Use

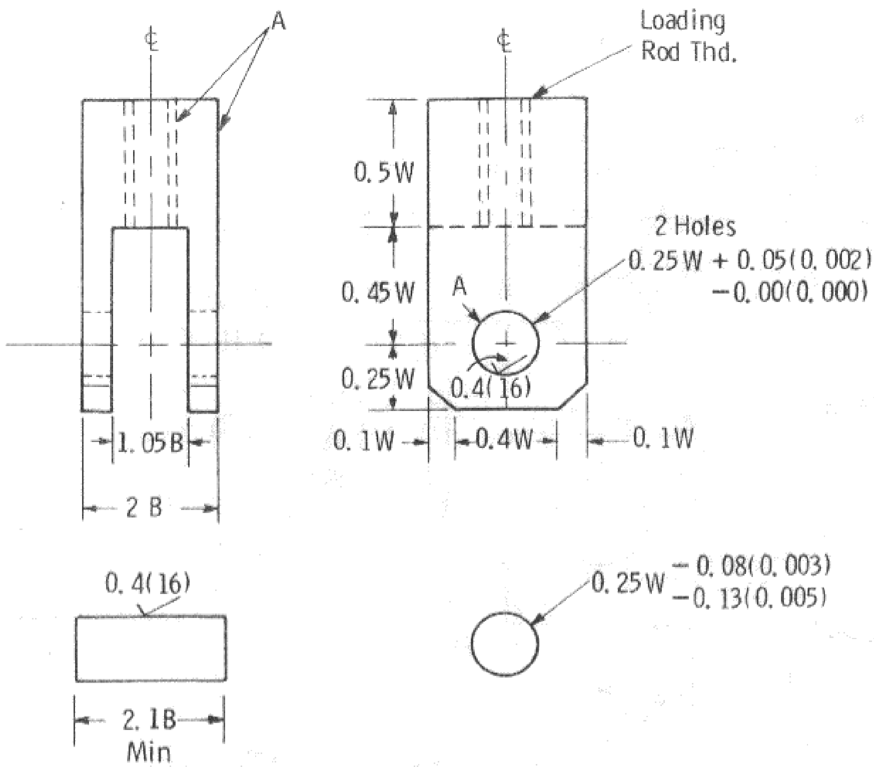
Fatigue crack growth rate can be expressed as a function of crack-tip stress intensity range, da/dN versus ΔK, characterizes a material's resistance to stable crack extension under cyclic loading. Expressing da/dN as a function of ΔK provides results that are independent of the planar geometry, thus enabling the exchange and comparison of data obtained from a variety of specimen configuration and loading condition. Fatigue crack growth rate data are not always geometry-independent since thickness effects sometimes occur. However, the data on influence of thickness on fatigue crack growth rate are mixed. Fatigue crack growth rates have been reported to increase, decrease, or remain unaffected as specimen thickness is increased.

2.5.2 Test Purposes

This test method can establish the influence of fatigue crack growth on the life of component subjected to cyclic loading, provided data are generated under representative condition and combined with appropriate fracture toughness data (ASTM E399), defect characterization data, and stress analysis information.

2.5.3 Grips and Fixtures for C(T) Specimen

A clevis and pin assembly as shown in Figure 2.11 is used at both the top and bottom of the specimen to allow in plane rotation as the specimen is loaded. Suggested proportion and critical tolerances of the clevis and pin are given in terms of the specimen width, *W*, or the specimen thickness, *B*, since these dimensions may be varied independently within certain limits.



NOTE 1—Dimensions are in millimetres (inches).
NOTE 2—*A*-surfaces shall be perpendicular and parallel as applicable to within 0.05 mm (0.002 in.), TIR.

Figure 2.11: Clevis and Pin Assembly for Gripping C(T) Specimen [8]

2.5.4 Specimen Configuration, Size, and Preparation

The geometry of standard C(T) specimen is as shown in Figure 2.12. It is required that the machined notch, a_n in the C(T) specimen be at least $0.2W$ in length so that the K-calibration is not influenced by small variation in the location and dimensions of the loading-pin holes.

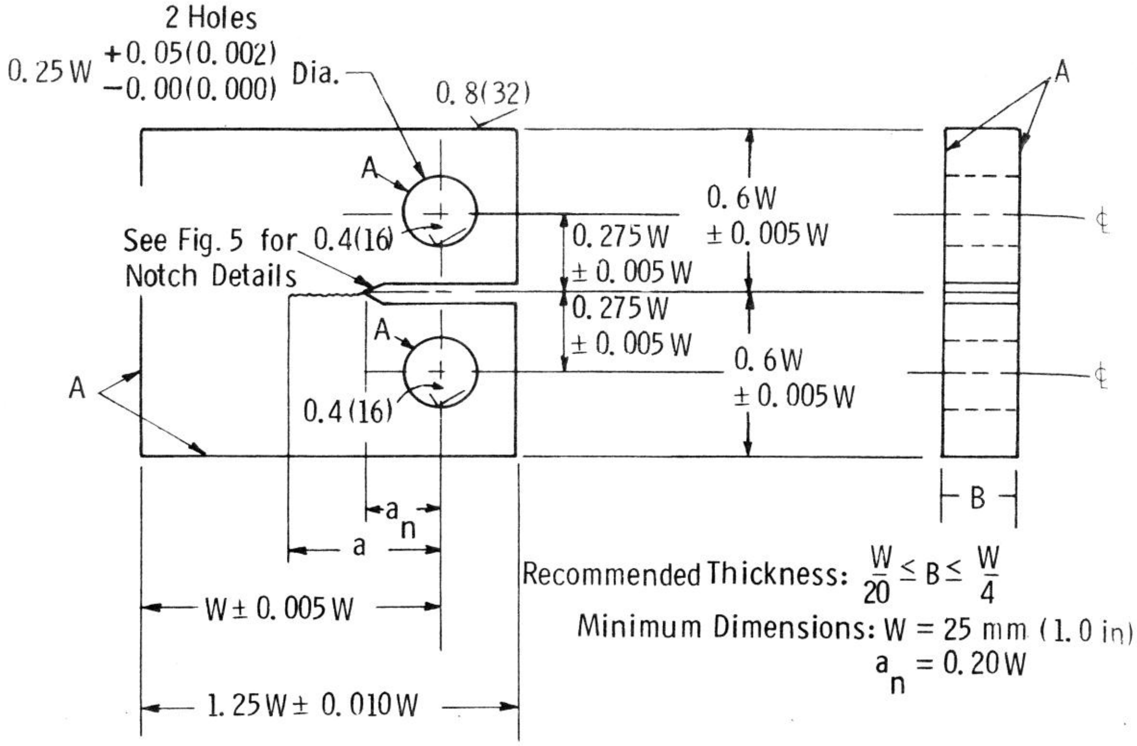


Figure 2.12: Standard C(T) Specimen for Fatigue Crack Growth Rate Testing [8]

The thickness, B, and width, W, may be varied independently within the following limits, which are based on specimen buckling and through-thickness-crack-curvature consideration. For C(T) specimens it is recommended that thickness be within the range $W/20 \leq B \leq W/4$.

The machined notch for either of the standard specimens may be made by EDM, milling, broaching, or saw cutting. The following notch preparation procedures are suggested to facilitate fatigue precracking in various materials shown in Table 2.2.

Table 2.2: Notch Preparation Procedures [8]

Method	Specification
EDM	$\rho < 0.25$ mm, high-strength steels
Mill or Broach	$\rho \leq 0.25$ mm, aluminum alloys
Grind	$\rho \leq 0.25$ mm, low or medium strength steels
Saw cut	Aluminum alloys

2.5.5 Test Procedure

In terms of the number of test, variability in da/dN data at a given ΔK may vary by a factor of 2. It is a good practice to conduct replicate tests. When this is impractical, tests should be planned such that regions of overlapping da/dN versus ΔK data are obtained. For the specimen measurement, all the dimensions shall be within the tolerance given.

2.5.6 Measurement of Crack Length via Compliance Methods

Fatigue crack length measurements are made as a function of elapsed cycles by means of visual, or equivalent, technique capable of resolving crack extensions of 0.10 mm, or 0.002W, or whichever is greater. In this project, crack size is measured via Epsilon Extensometer and graph Crack Opening Displacement versus Crack Length will be plotted. Crack length will increase proportionally with crack opening displacement. Crack length, a can be calculated from COD reading using equation below [9]:

$$\frac{a}{W} = A_0 + A_1U + A_2U^2 + A_3U^3 + A_4U^4 + A_5U^5 \tag{5}$$

Where,

A = constant

a = crack length, mm

W= specimen width, mm

$$U = \frac{1}{\left(\frac{EBv}{P}\right)^{1/2} + 1}$$

E = modulus of elasticity, Gpa

B = specimen thickness, mm

v = COD reading, mm

P = max load, kN

CHAPTER 3

METHODOLOGY

3.1 PROJECT FLOW CHART

Figure 3.1 shows the Project Flow Chart that contains the engineering drawing process, fabrication process and testing process for this project. For FYP 1, literature review was carried out covering fracture toughness, fatigue crack growth, crack measurement via crack opening displacement, and the related standards of ASTM E399 and ASTM E647. The sources for the literature review are taken from several types of references such as books, websites and journals.

The engineering drawing process was carried out by producing the drawings for test specimen, integral knife edge, and gage beam. The dimension for the test specimen and integral knife edges were based on ASTM E399. Any changes in the dimensions were considered as long as they were in the allowable range. The gage beam fabrication was the most critical task since it was to be connected to the test specimen and Epsilon extensometer. Since the gage was fixed to the extensometer by two screws, the precision of the screw holes were very important.

The test specimens with the integral knife edges were made from mild steel and aluminum. The processes of fabrication of the test specimens were carried out using Electrical Discharge Machining (EDM) Wire Cut. Stainless steel was used to fabricate the gage beam via EDM wire cut. Clevises were already fabricated from the previous project.

Firstly the tests for fatigue crack growth were run. Before the real test was conducted, several tests for static load were done to gather some data regarding the material, machine accessories and machine procedure. If the test was completed without any problem, the machine was ready for fatigue crack growth.

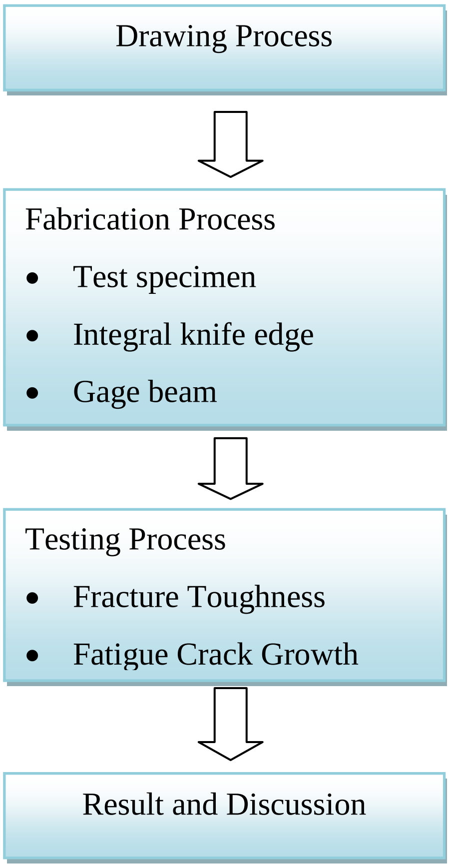


Figure 3.1: Project Flow Chart

3.2 GANTT CHART

Gantt chart can be found in Figure 3.2 and Figure 3.3. The Gantt chart contains all the activities involved in FYP 1 and also FYP 2.

No	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topic														
2	Literature review research														
3	Seminar														
4	Drawing the C(T) specimen and integral knife edge														
5	Drawing the gage beam														
6	Fabrication of the specimen														

Figure 3.2 : Gantt Chart for Final Year Project 1

No	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Calibration of the extensometer														
2	Testing for jig and specimen sample														
3	Fatigue Precrack														
4	Seminar														
5	Fracture Toughness test														
6	Fatigue Crack Growth test														

Figure 3.3 : Gantt Chart for Final Year Project 2

	In Progress
	Completed

3.3 TOOLS SPECIFICATION AND MANUFACTURING PROCESS

Test Specimen Estimation

For a valid result, what we need is for the specimen thickness, *B* and the crack length, *a* exceed $2.5(K_{Ic}/\sigma_{YS})^2$, where σ_{YS} is the 0.2% offset yield strength of the material for the temperature and loading rate of the test. The valid value for K_{Ic} is obtained from the estimated value K_{Ic} for the material. Below is the specification of the specimen based on the ASTM requirement.

Test Specimen Specification

Compact Tension had been choose as the test specimen configuration as shown in Figure 3.4 and the fabrication value can be found in Table 3.1. Starter notch and fatigue crack for straight through notch for this specimen were based on Figure 3.5 and the fabrication value can be found in Table 3.2. As for the integral knife edge, the specification shown in Figure 3.6 and the fabrication value showed in Table 3.3.

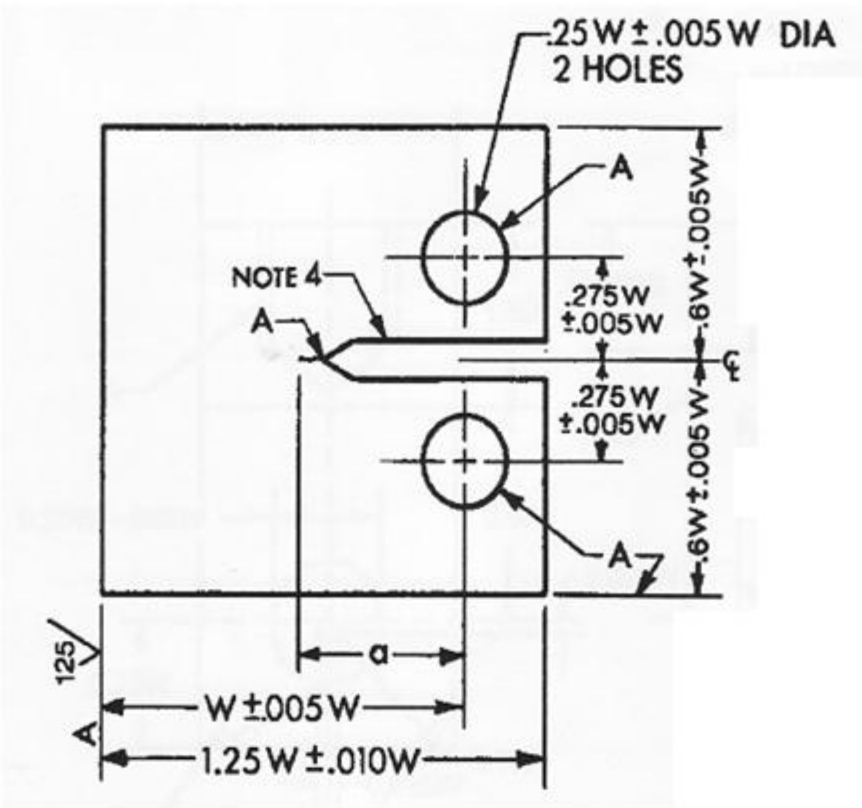


Figure 3.4: Compact Tension Specimen Standard Proportion and Tolerance [7]

Table 3.1: Compact Tension specification

Properties	ASTM Requirement	Fabrication Value
Material	Any available material	Aluminum and mild steel
Width, *W*	Any value	56mm
Crack length, *a*	$0.45W \leq a \leq 0.55W$ $25.2\text{mm} \leq a \leq 30.8\text{mm}$	29.9mm
Distance between centers of pin to the fatigue crack	$0.275W$ 15.4mm	15.4mm
Pin diameter	$0.25W$ 14.0mm ± 0.1mm	15mm

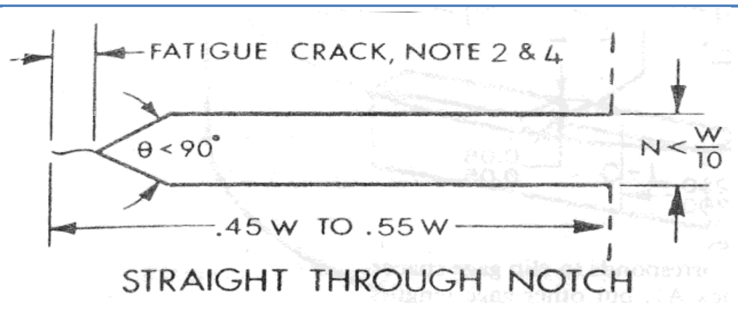


Figure 3.5: Starter Notch and Fatigue Crack for Straight Through Notch [7]

Table 3.2: Starter Notch and Fatigue Crack specification

Properties	ASTM Requirement	Fabrication Value
Notch, *N*	$N<W/10$ $N<5.6\text{mm}$	5.0mm
Angle of V-notch, *θ*	$\theta < 90^o$	80^o
Fatigue crack extension	At least $0.025W$ ≥1.4mm	1.4mm

Integral Knife Edge Specification

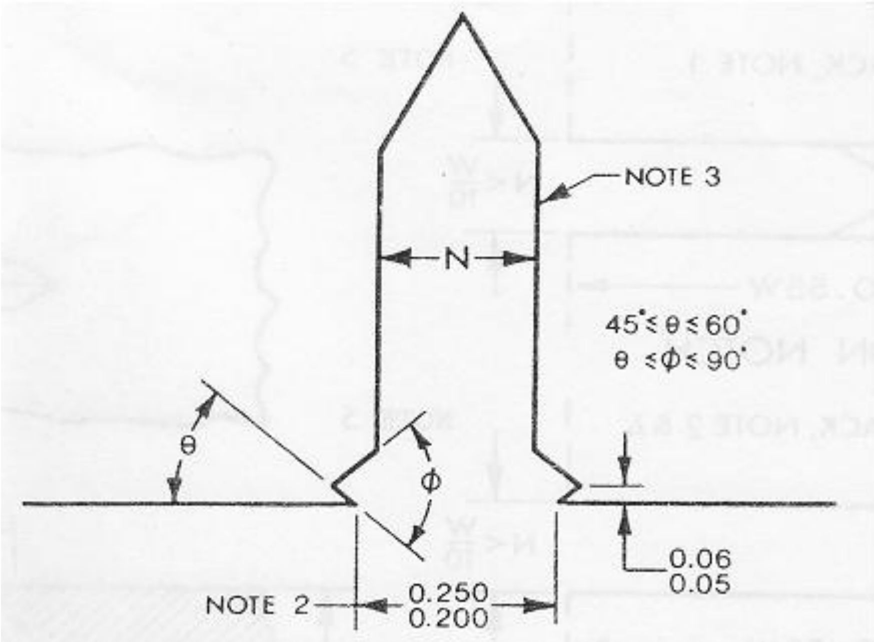


Figure 3.6: Integral Knife Edge Design [7]

Table 3.3: Integral Knife Edge specification

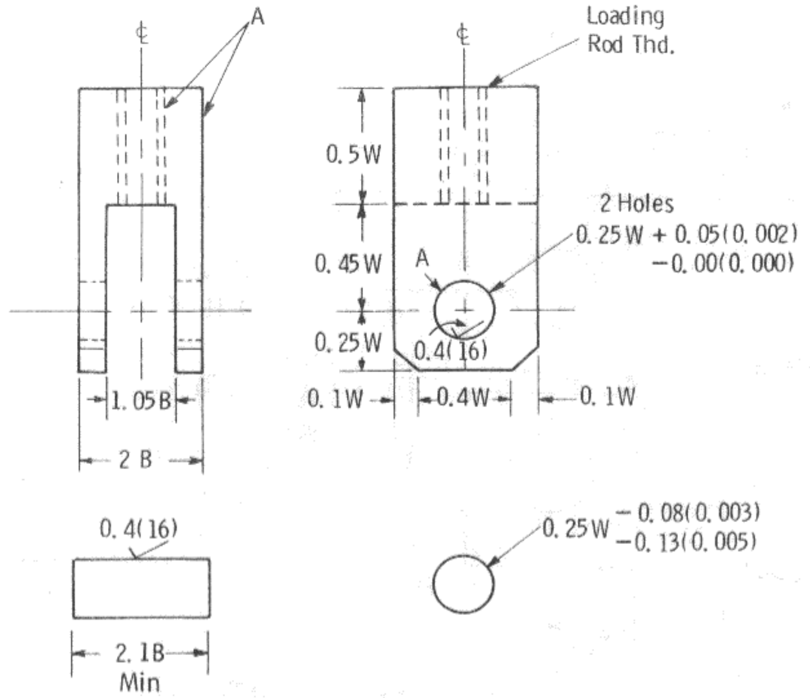
Properties	ASTM Requirement	Fabrication Value
$\boldsymbol{\theta}$	$45^{o} \leq \theta \leq 60^{o}$	60^{o}
$\boldsymbol{\varphi}$	$\theta \leq \varphi \leq 90^{o}$	90^{o}

Test Specimen and Integral Knife Edge Fabrication

The specimens and integral knife edge are fabricated using Electrical Discharge Machining Wire Cut.

Clevis Specification

Since the clevis and pin design from the previous project has been made and the specification is the same, there is no need to fabricate new clevis and pin. Figure 3.7 and Table 3.4 showed the specification for the clevis.



NOTE 1—Dimensions are in millimetres (inches).
NOTE 2—*A*-surfaces shall be perpendicular and parallel as applicable to within 0.05 mm (0.002 in.), TIR.

Figure 3.7: Clevis and Pin Assembly for Gripping C(T) Specimen [8]

Table 3.4: Clevis specification

Properties	ASTM Requirement	Fabrication Value
Bottom through hole	$0.25W$ (± 0.1)	15 mm
Clevis bottom opening	$\geq 1.05B$	29 mm
Top cavity	-	Outer diameter = 43.1 mm Inner diameter = 36 mm
Bottom diameter	$\geq 2B$	57 mm

Pin Specification

Pin diameter should be at 0.25W. Therefore, the test specimen pin diameter is 14.0 ± 0.1mm equal to 15mm.

3.4 CALIBRATION OF EXTENSOMETER

Before the extensometer can be used, some calibrations need to be done. The purpose of this task is to simulate real time testing and to come out with a correction factor for the extensometer value. Calibration of the extensometer will be done using a modified micrometer. The micrometer's spindle and anvil were attached a sharp edge of aluminum rod with a diameter of 6.3 mm as shown in Figure 3.8. The extensometer gage will be put at the center of the spindle and anvil. There will be two steps involve which are the increment and decrement of readings. Basic increment of ±0.050mm will used throughout the task.

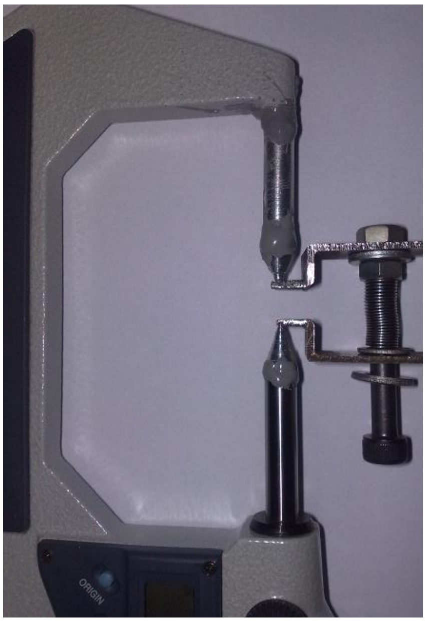


Figure 3.8: Calibration of extensometer

3.5 FATIGUE PRECRACK

A fatigue precrack is produced by cyclically loading the notched specimen ratio of minimum to maximum stress between -1 and +0.1 for a number of cycles usually between 10^4 and 10^6 depending on specimen size, notch preparation and stress intensity level [7]. The initial value of the maximum fatigue load should be calculated from the K of the specimen and notch dimension. It is suggested that this load to be selected so the maximum stress intensity factor of the fatigue cycle does not exceed 80% of the estimated K_{Ic} value of the material. If the final precrack is 2.52 cm for aluminum sample, the process can be divided into two phase. Firstly for the precrack until 2.00 cm by substituting the value of a equal to 2.00 cm into the below equation. The second phase would be until precrack equal to the desired length which was 2.52 cm. In order to determine the maximum load, refer to Table 3.5 and Table 3.6. Any load can be used as long as the chosen load did not exceed 80% of the K_Q of the next phase. As for this situation, maximum load of 10.80 kN can be used since less than 80% of K_Q for crack length of 25.2 cm.

$$P_Q = \frac{K_Q B\sqrt{W}}{f(^a/_W)} \tag{6}$$

Where,

P_Q = Max load, kN

K_Q = portion of stress intensity factor, MPa.m$^{1/2}$

a = crack length (cm)

$$f(a/W) = \frac{3(a/W)^{\frac{1}{2}}[1.99-(a/W)(1-a/W)x(2.15-3.93a/w+2.7a^2/W^2)]}{2(1+2a/W)(1-a/W)^{\frac{3}{2}}} \tag{7}$$

Aluminum:

K_{Ic} = 55 MPa.m$^{1/2}$

Crack length, a = 2.00 cm

Table 3.5: Aluminum first phase precrack determination

Percent Kic	Kmax	Pmax	Pmin
0.80	44.00	14.39	1.44
0.75	41.25	13.49	1.35
0.70	38.50	12.59	1.26
0.65	35.75	11.70	1.17
0.60	33.00	10.80	1.08
0.55	30.25	9.90	0.99
0.50	27.50	9.00	0.90

Crack length, a = 2.52 cm

Table 3.6: Aluminum last phase precrack determination

Percent Kic	Kmax	Pmax	Pmin
0.80	44.00	11.24	1.12
0.75	41.25	10.53	1.05
0.70	38.50	9.83	0.98
0.65	35.75	9.13	0.91
0.60	33.00	8.43	0.84
0.55	30.25	7.73	0.77
0.50	27.50	7.02	0.70

CHAPTER 4

RESULT AND DISCUSSION

4.1 FABRICATION OF THE SPECIMEN

Samples were fabricated using EDM machine for mild steel and aluminum. The specimens are shown in Figure 4.1. The detail of the drawing can be seen in Appendix 1.

Figure 4.1: Specimen of aluminum compact tension

4.2 FABRICATION OF THE GAGE BEAM

The gage beams were fabricated using EDM machine. Stainless steel was chosen for the fabrication material. The gage beam is shown in the Figure 4.2.

Figure 4.2: Gage beam

4.3 CALIBRATION OF EXTENSOMETER

Graph of Extensometer reading versus Micrometer reading were plots for each increment decrement and also for both. The results obtained for the first trial can be seen in Figure 4.3 and Figure 4.4 while results for the second trial can be seen in Figure 4.5 and Figure 4.6.

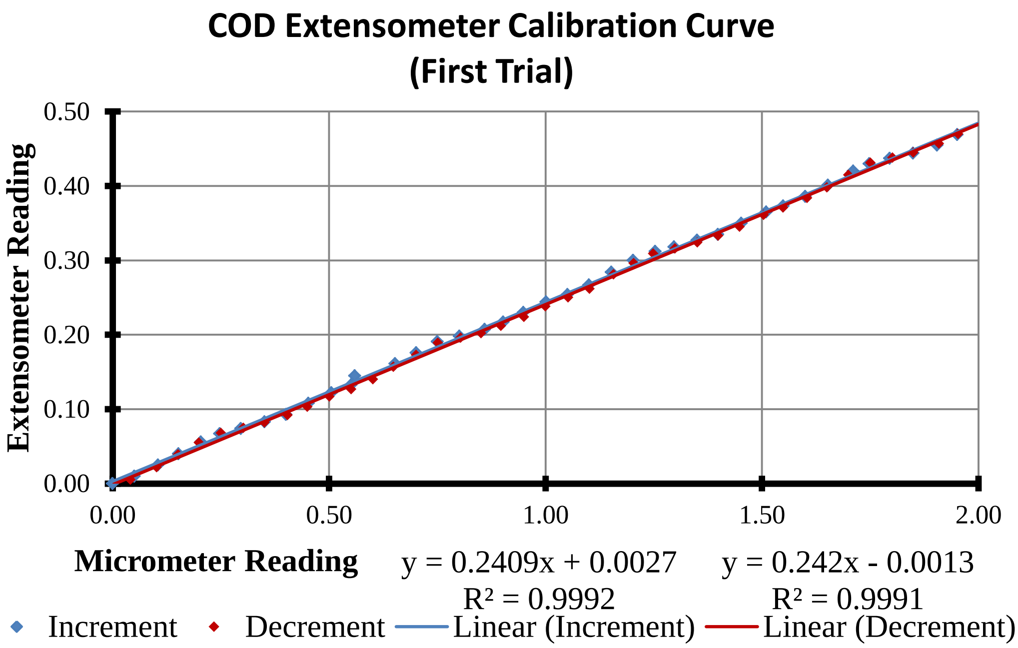


Figure 4.3: COD Extensometer Calibration Curve for increment and decrement (First Trial)

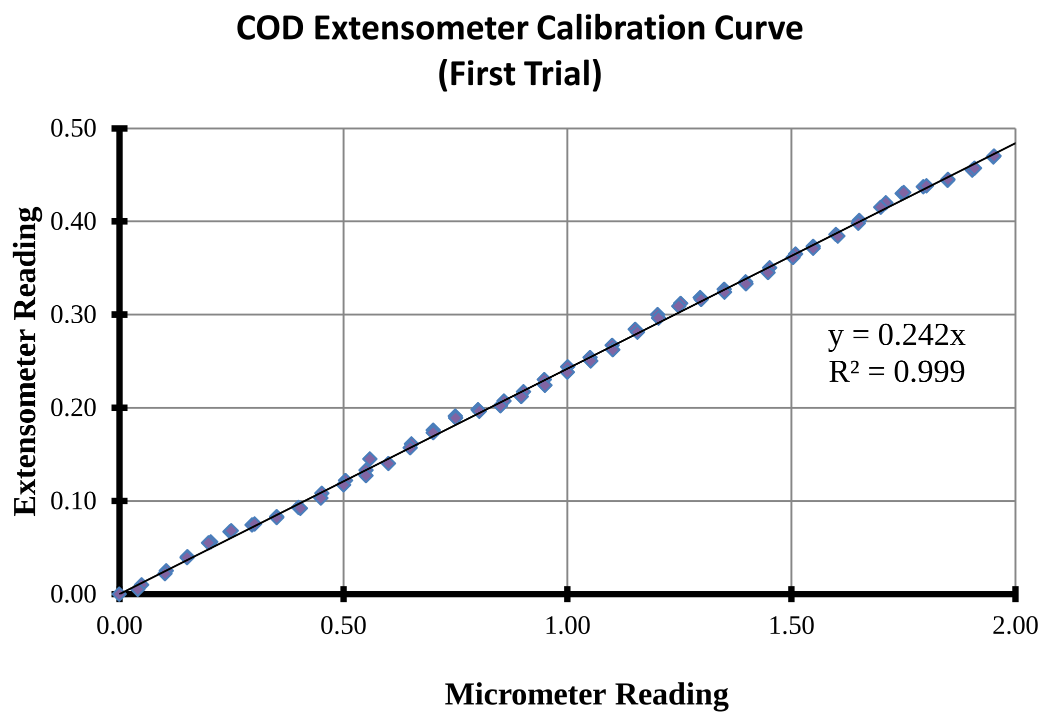


Figure 4.4: COD Extensometer Calibration Curve (First Trial)

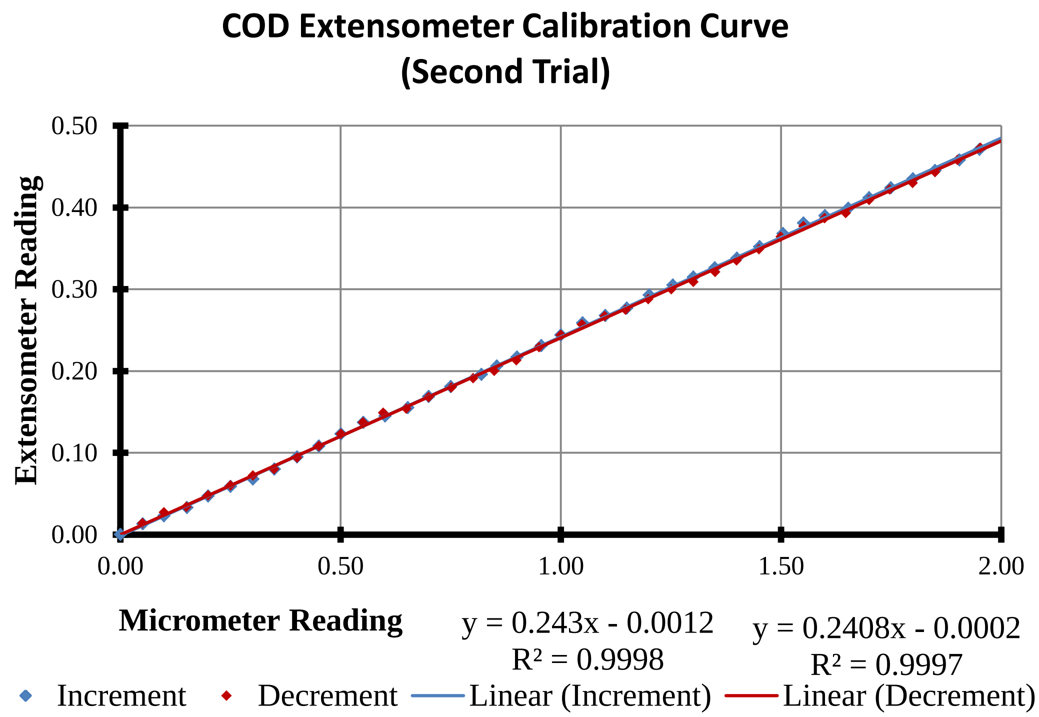


Figure 4.5: COD Extensometer Calibration Curve for increment and decrement (Second Trial)

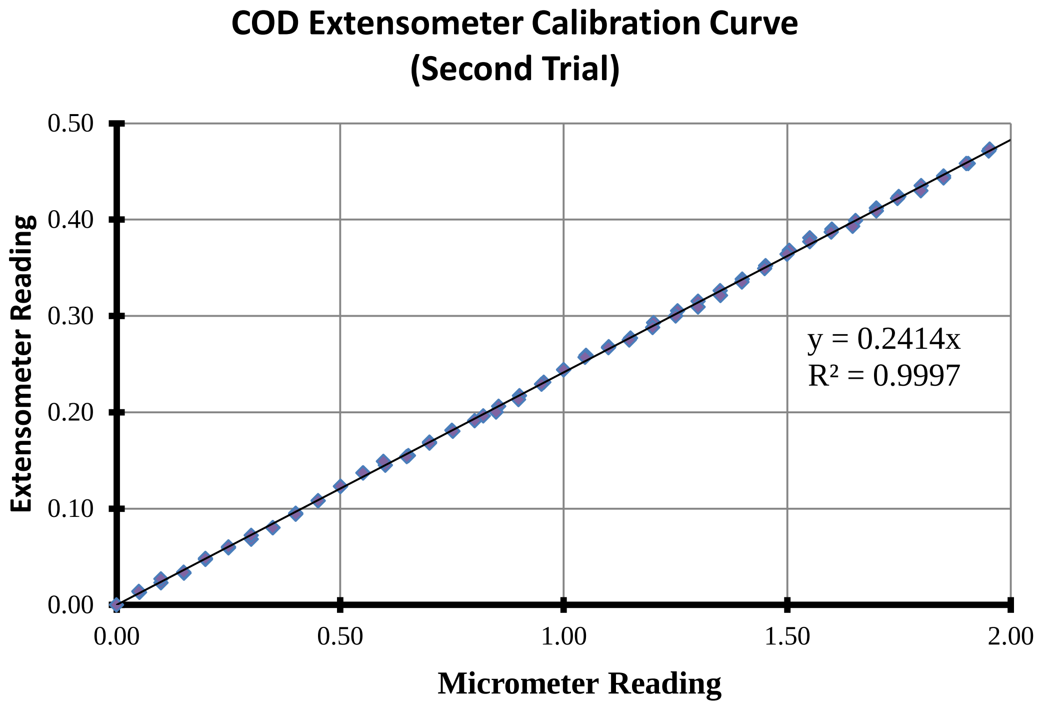


Figure 4.6: COD Extensometer Calibration Curve (Second Trial)

By taking the average of graph gradient,

$$Correction\ Factor = \frac{0.242 + 0.241}{2}$$

$$= 0.2415$$

COD reading with correction factor will be,

$$COD = 4.1408 \times Extensometer \quad (8)$$

4.4 FATIGUE PRECRACK

A fatigue precrack is produced by cyclically loading the notched specimen ratio of minimum to maximum stress between -1 and +0.1 for a number of cycles usually between 10^4 and 10^6 depending on specimen size, notch preparation and stress intensity level [7]. Example of specimen with a hairline crack is shown in Figure 4.7.

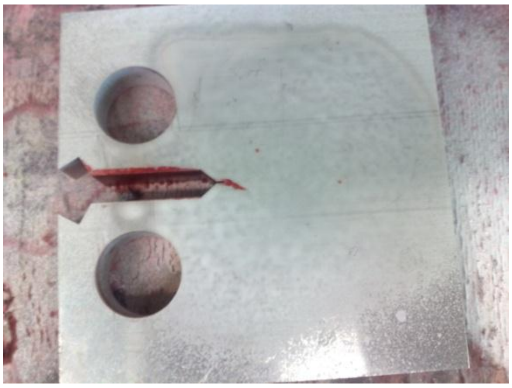


Figure 4.7: Hairline crack for aluminum sample

4.5 FRACTURE TOUGHNESS TEST

4.5.1 Validity Check

Condition 1:

$$\frac{P_{max}}{P_Q} < 1.10$$

Condition 2:

$$2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2 < a_0, B \text{ and } W - a_0$$

$$K_{1C} = K_Q = \frac{P_Q}{B\sqrt{W}} f\left({}^{a}/_{W}\right)$$

Where,

$$f\left({}^{a}/_{W}\right) = \frac{(2 + a/W)(0.886 + 4.64\, a/W - 13.32\, a^2/W^2 + 14.72\, a^3/W^3 - 5.6\, a^4/W^4)}{(1 - a/W)^{3/2}}$$

Figure 4.8 shows the typical plot for load versus COD from the fracture toughness test. Linear line with a slope of 95% from the original slope was plotted and the intercept value obtained as the P_Q.

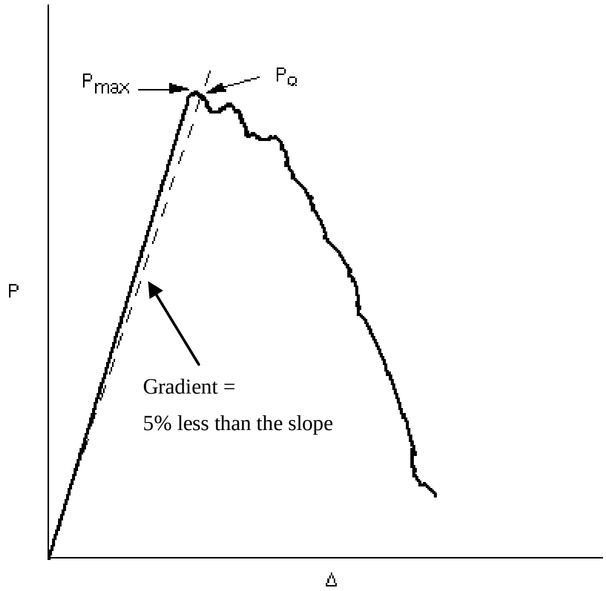


Figure 4.8: Typical load-COD plot obtained in a fracture toughness experiment [10]

4.5.2 Fracture Toughness Test on Aluminum Sample

Sample 1:

Crack length, a = 28 mm

Conditional Load, P_Q = 12.427 kN

Condition 1:

$$\frac{14.57}{12.427} = 1.172 > 1.10$$

Not valid

Condition 2:

$$2.5\left(\frac{59.61}{414}\right)^2 = 0.05 > 0.009$$

Not valid

Figure 4.9 shown the load versus COD reading obtained for sample 1.

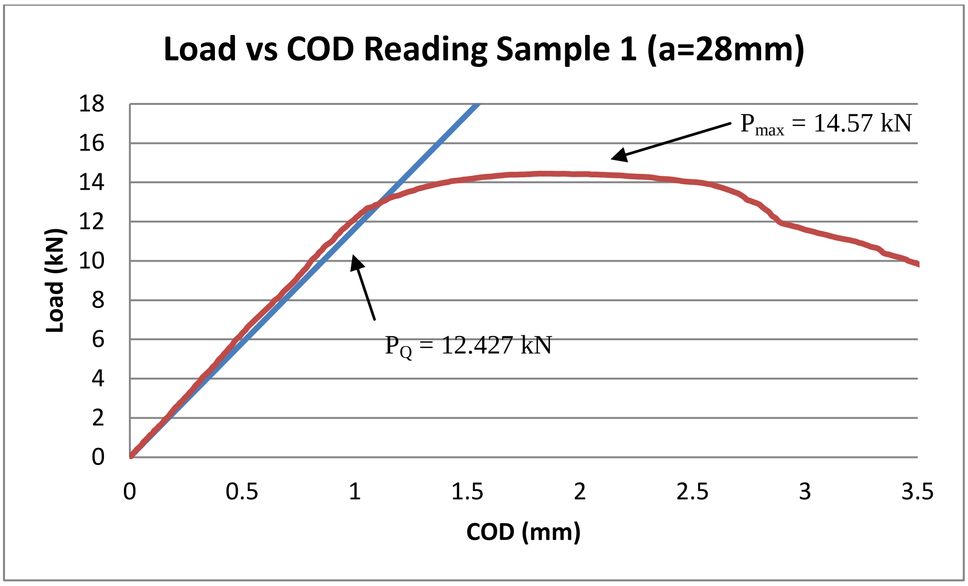


Figure 4.9: Graph of Load vs COD Reading for Sample 1(Aluminum)

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left({}^{a}/_{W}\right) \qquad f\left({}^{a}/_{W}\right) = 9.659079$$

$$= \frac{12427}{0.009\sqrt{0.056}}(9.659079)$$

$$= 56.36\ MPa\sqrt{m}$$

Sample 2:

Crack length, a = 27 mm

Conditional Load, P_Q = 12.744 kN

Condition 1:

$$\frac{14.145}{12.744} = 1.11 > 1.10$$

Not valid

Condition 2:

$$2.5\left(\frac{53.448}{414}\right)^2 = 0.04 > 0.009$$

Not valid

Figure 4.10 shown the load versus COD reading obtained for sample 2.

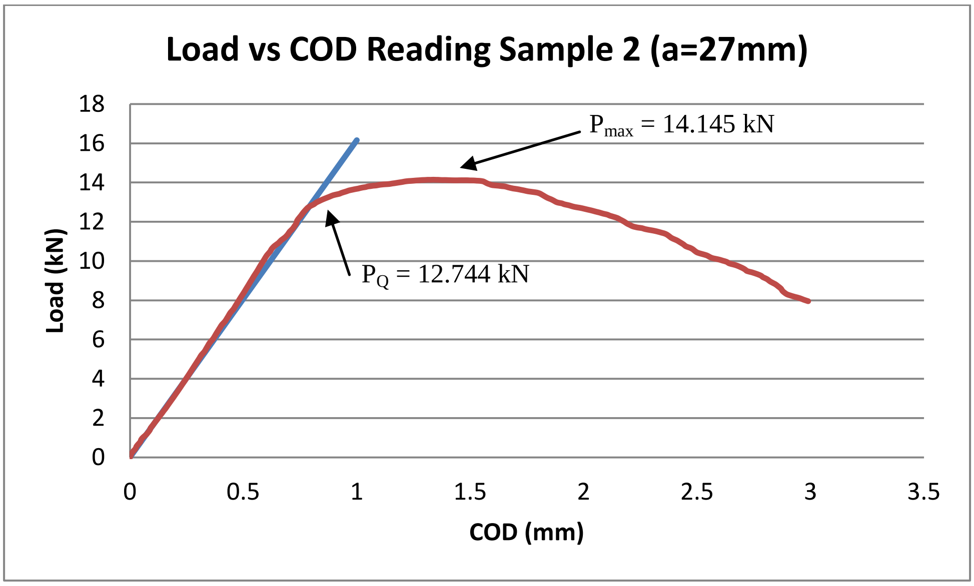


Figure 4.10: Graph of Load vs COD Reading for Sample 2(Aluminum)

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left({}^{a}/_{W}\right) \qquad f\left({}^{a}/_{W}\right) = 9.151308$$

$$= \frac{12744}{0.009\sqrt{0.056}}(9.151308)$$

$$= 54.76\ MPa\sqrt{m}$$

4.5.3 Fracture Toughness Test on Mild Steel Sample

Sample 1:

Crack length, a = 30 mm

Conditional Load, P_Q = 12.814 kN

Condition 1:

$$\frac{14.937}{12.814} = 1.17 > 1.10$$

Not valid

Condition 2:

$$2.5\left(\frac{65.147}{448}\right)^2 = 0.05 > 0.009$$

Not valid

Figure 4.11 shown the load versus COD reading obtained for sample 1.

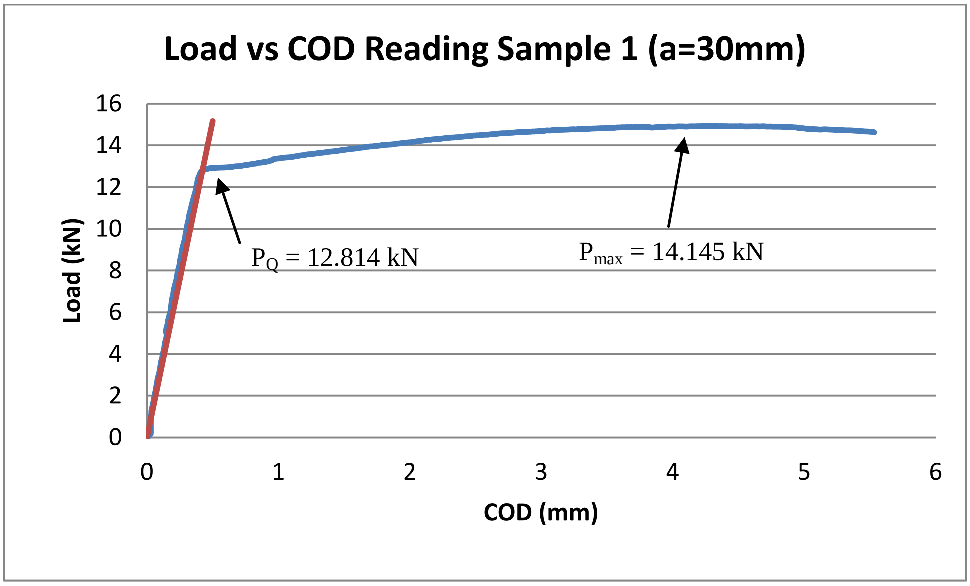


Figure 4.11: Graph of Load vs COD Reading for Sample 1(Mild Steel)

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left({}^{a}/_{W}\right) \qquad f\left({}^{a}/_{W}\right) = 10.8279$$

$$= \frac{12814}{0.009\sqrt{0.056}}(10.8279)$$

$$= 65.16\ MPa\sqrt{m}$$

Sample 2:

Crack length, a = 25 mm

Conditional Load, P_Q = 16.024 kN

Condition 1:

$$\frac{20.901}{16.024} = 1.30 > 1.10$$

Not valid

Condition 2:

$$2.5\left(\frac{65.147}{448}\right)^2 = 0.05 > 0.009$$

Not valid

Figure 4.12 shown the load versus COD reading obtained for sample 2.

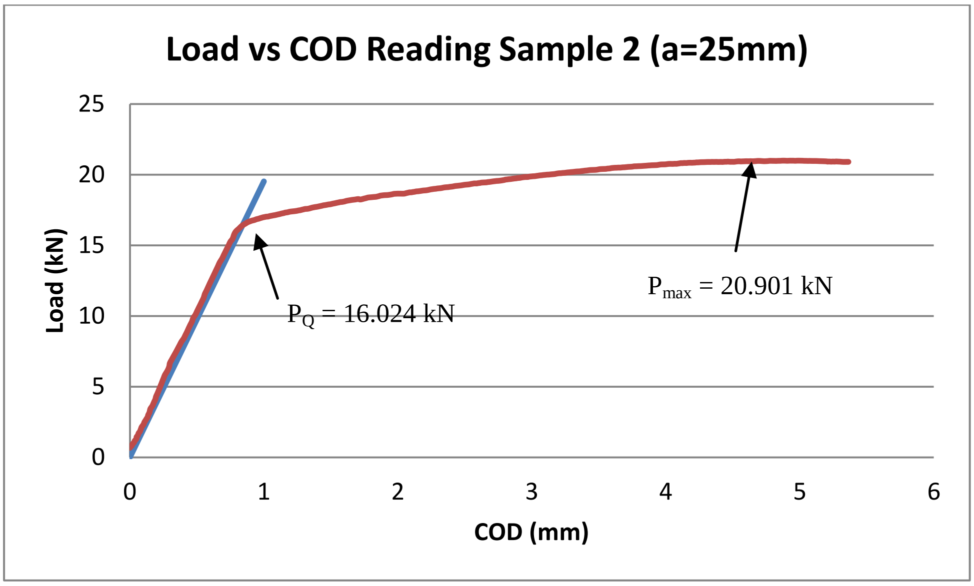


Figure 4.12: Graph of Load vs COD Reading for Sample 2(Mild Steel)

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left({}^{a}/_{W}\right) \qquad f\left({}^{a}/_{W}\right) = 8.34$$

$$= \frac{16024}{0.009\sqrt{0.056}}(8.34)$$

$$= 62.748\ Mpa\sqrt{m}$$

4.6 FATIGUE CRACK GROWTH TEST

4.6.1 Fatigue Crack Growth Test on Aluminum Sample

Sample 1: (8843 cycle)

Max load = 8.3kN

Min load = 0.83kN

Sample 2: (17450 cycle)

Max load = 6.73kN

Min load = 0.673kN

Using compliance, COD reading were converted to crack length using below equation:

$$\frac{a}{W} = A_0 + A_1U + A_2U^2 + A_3U^3 + A_4U^4 + A_5U^5 \tag{5}$$

where the constants for the compliance equation is given in Table 4.1 below.

Table 4.1: Interpolating polynomials for *a/W*

Specimen	A_0	A_1	A_2	A_3	A_4	A_5
C(T)	1.000	-5.005	31.752	-353.6	1664.381	-2747.965

The empirical parameter U is given by:

$$U = \frac{1}{\left(\frac{EBv}{P}\right)^{1/2} + 1} = \frac{1}{\left(\frac{69(9)v}{8.3@6.73}\right)^{1/2} + 1}$$

The resulting curve of Crack Length versus Number of Cycles is shown in Figure 4.13.

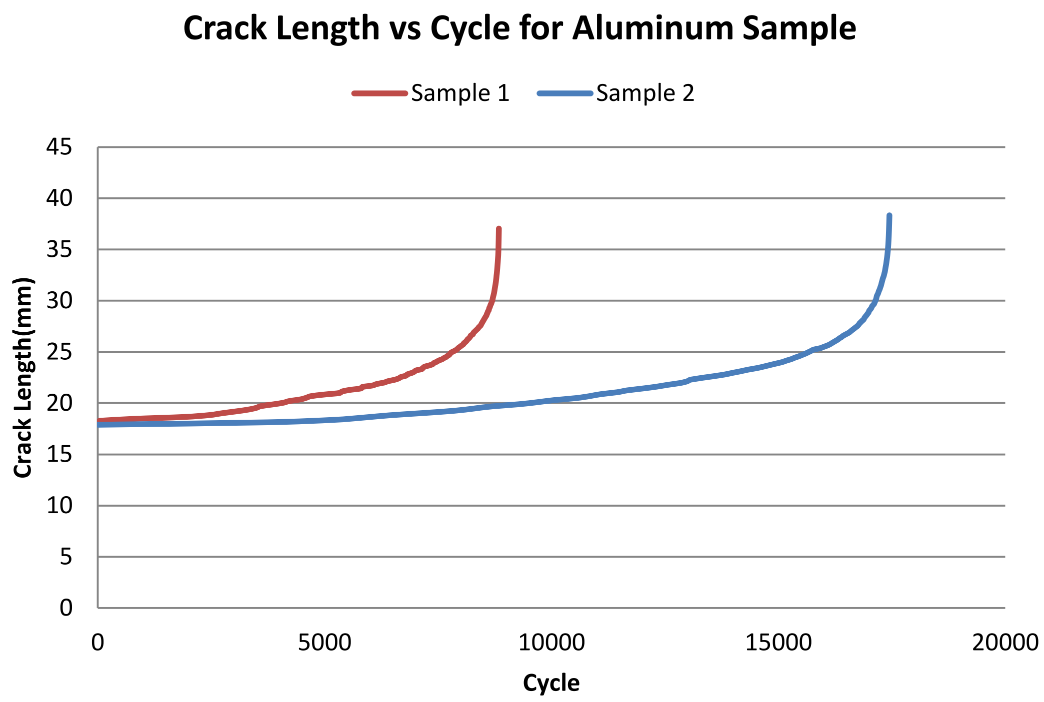


Figure 4.13: Graph of Load Crack Length vs Cycle for Aluminum Sample

The stress intensity range ΔK can be calculated using equation below,

$$\Delta K = \frac{\Delta P}{B\sqrt{W}}\frac{(2+a)}{(1-a)^{\frac{3}{2}}}(0.886 + 4.64a - 13.32a^2 + 14.72a^3 - 5.6a^4) \tag{6}$$

while the da/dN value are taken from the slope of the graph crack length versus cycle. The resulting Paris curve of da/dN vs ΔK is shown in Figure 4.14 while the Paris constants C and m are given in Table 4.2.

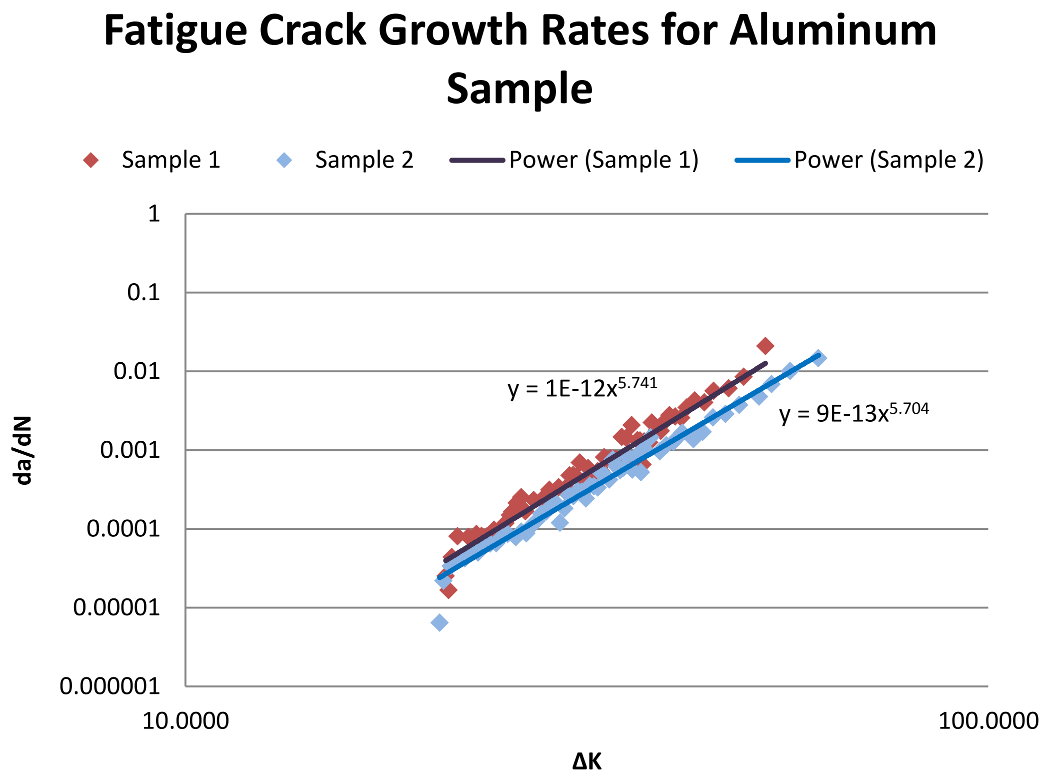


Figure 4.14: Graph of Fatigue Crack Growth Rates for Aluminum Sample

Fatigue crack growth rates can be expressed as,

$$\frac{da}{dN} = C(\Delta K)^m \tag{2}$$

Table 4.2: Fatigue Crack Growth Rates for Aluminum sample

Aluminum	*C*	*m*	Fatigue Crack Growth Rates (mm/cycle)
Sample 1	1×10^{-12}	5.741	$\frac{da}{dN} = 1x10^{-12}(\Delta K)^{5.741}$
Sample 2	9×10^{-13}	5.704	$\frac{da}{dN} = 9x10^{-13}(\Delta K)^{5.704}$

4.6.2 Fatigue Crack Growth Test on Mild Steel Sample

Results for steel were obtained in similar manner. The data and calculations are as follows.

Sample 1: (26371 cycle)	Sample 2: (17481 cycle)
Max load = 12.84kN	Max load = 14.12kN
Min load = 1.284kN	Min load = 1.412kN

Table 4.3: Interpolating polynomials for *a/W*

Specimen	A_0	A_1	A_2	A_3	A_4	A_5
C(T)	1.000	-5.005	31.752	-353.6	1664.381	-2747.965

Empirical parameter:

$$U = \frac{1}{\left(\frac{EBv}{P}\right)^{1/2} + 1} = \frac{1}{\left(\frac{170(9)v}{12.84@14.12}\right)^{1/2} + 1}$$

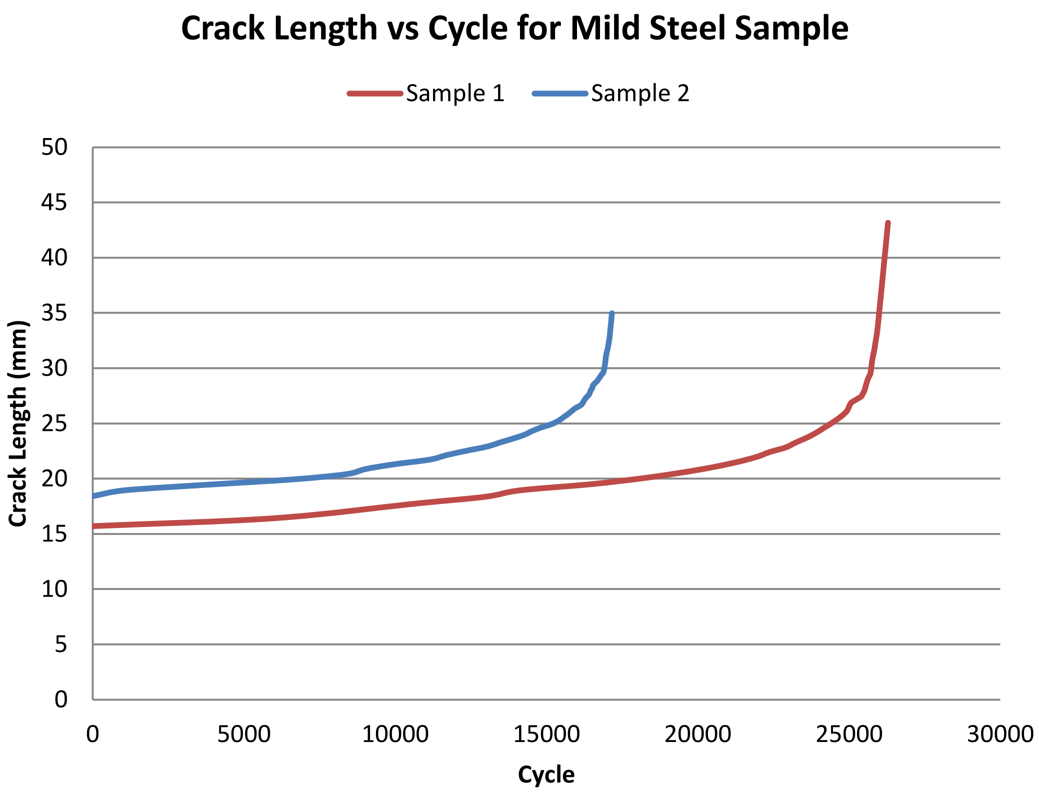


Figure 4.15: Graph of Load Crack Length vs Cycle for Mild Steel Sample

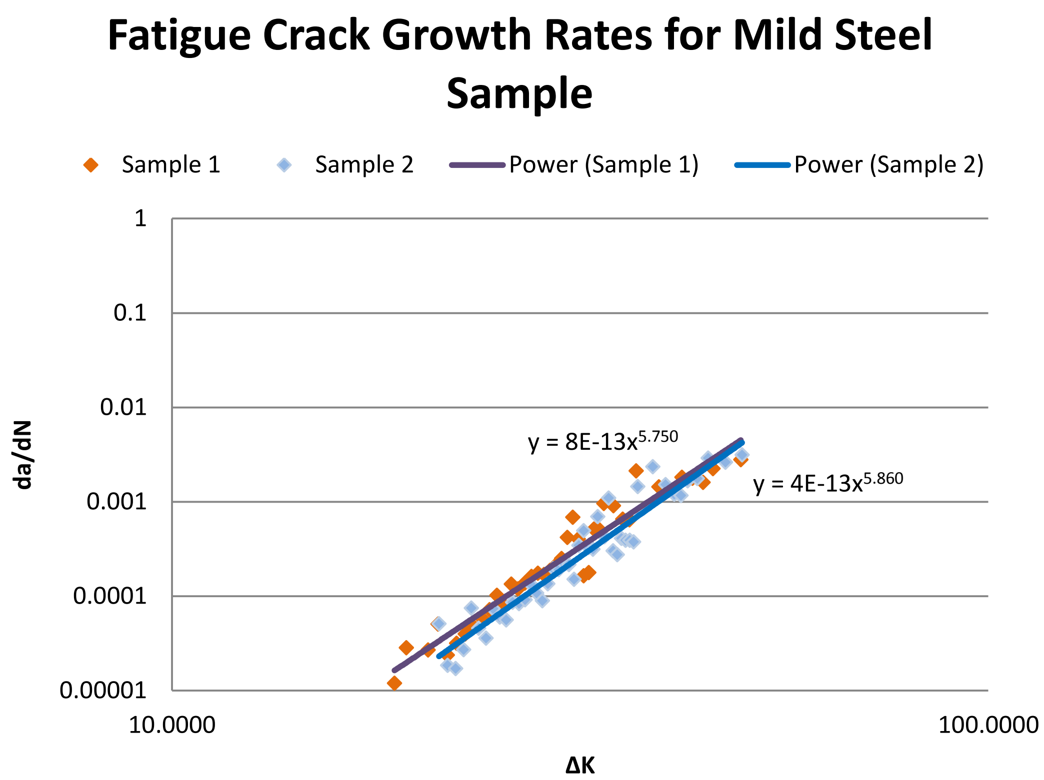


Figure 4.16: Graph of Fatigue Crack Growth Rates for Mild Steel Sample

Table 4.4: Fatigue Crack Growth Rates for Mild Steel sample

Mild Steel	*C*	*m*	Fatigue Crack Growth Rates (mm/cycle)
Sample 1	$8x10^{-13}$	5.750	$\frac{da}{dN} = 8x10^{-13}(\Delta K)^{5.750}$
Sample 2	$4x10^{-13}$	5.860	$\frac{da}{dN} = 4x10^{-13}(\Delta K)^{5.860}$

4.7 DISCUSSIONS

4.7.1 Graph Errors

The R-squared statistic measures how well the data fit the model of a straight line. The data would better fit the linear model if the value closer to 1.0. Load versus COD graph is supposed to have a straight line before the plastic deformation occur. Figure below shows an example of R^2=0.999. That means all the points are close to the theoretical values and concluded that this setup can be use for advanced material characterization.

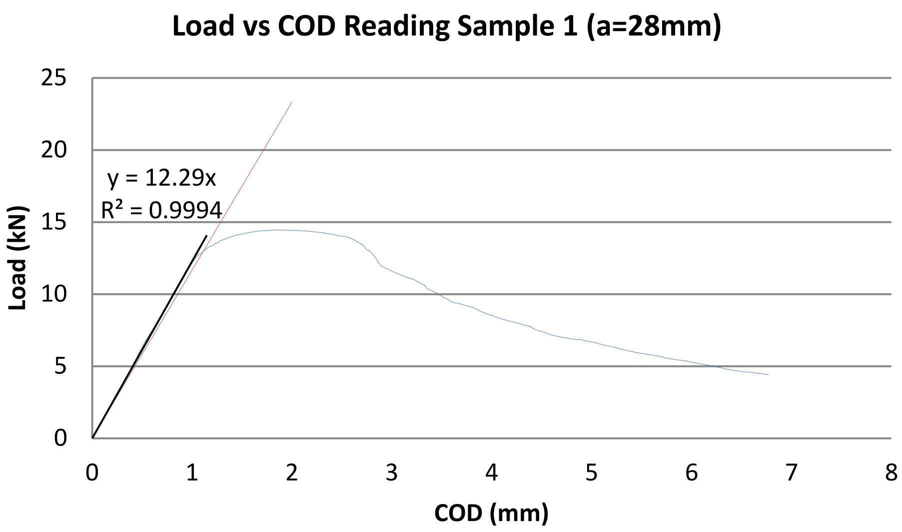


Figure 4.17: Graph error of Load vs COD Reading for Sample 1(Aluminum)

4.7.2 Non-smooth Graph

Graph for Sample 1 mild steel during fatigue crack growth is not smooth enough due to several "pause" during the test. Other samples' tests were carried out without any obstruction. During the "pause", the sample will be dissembled from the test configuration. This error is due to the extensometer gauge was not in place properly after the "pause". Below is the sample for the error.

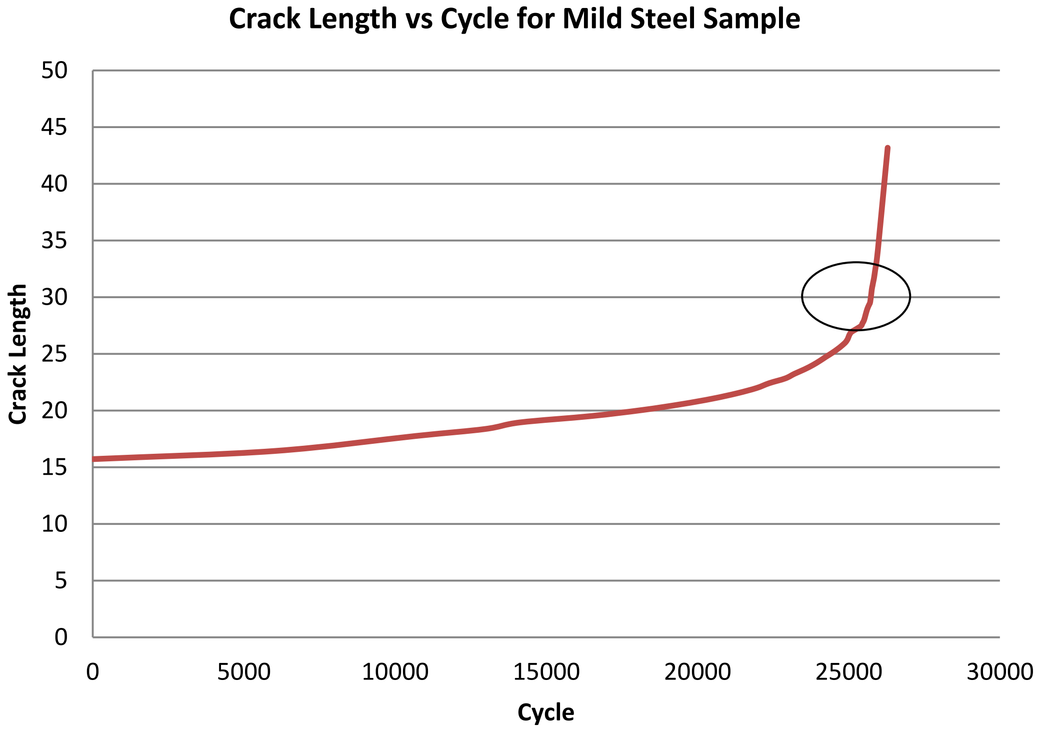


Figure 4.18: Non-smooth graph of crack vs cycle for mild steel sample during fatigue crack growth test

4.7.3 Fracture Toughness Results

Table 4.5: Fracture Toughness for Aluminum sample

Aluminum	**Fracture Toughness $(Mpa\sqrt{m})$**	**Theoretical Fracture Toughness $(Mpa\sqrt{m})$ [11]**
Sample 1	56.36	25-55
Sample 2	54.76	25-55

Table 4.6: Fracture Toughness for Mild Steel sample

Mild Steel	**Fracture Toughness $(Mpa\sqrt{m})$**	**Theoretical Fracture Toughness $(Mpa\sqrt{m})$ [11]**
Sample 1	65.147	50-95
Sample 2	62.748	50-95

The validity tests for all of the specimens failed and this meant that the K_Q values obtained are not the actual K_{IC} values. K_Q values obtained cannot be use as the material property but the values obtained are valid for thickness of the compact tension specimen used. In order for the K_Q to be valid K_{IC}, the specimen thickness needs to be increased until all the validity tests pass.

4.8 STANDARD OPERATING PROCEDURES

There are four main operating procedures that can be found in Appendix 3-6 which are:

1. General Procedures
2. Precrack Test
3. Fracture Toughness Test
4. Fatigue Crack Growth Test

These procedures are intended for future users of the accessories when performing the fracture toughness and fatigue crack growth tests.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In conclusion, the project objectives which are to implement COD and the compliance methods for crack length measurement during FCG test for C(T) specimens was successfully completed. In addition, the set up of the UTM for the FT and FCG tests, and to creation of the operating procedures for these tests for UTP's Materials Lab was also completed.

Many tasks had been performed such as fabrication of the accessories and test specimen, calibration of the extensometer, and fatigue precrack, in order to complete this project. The various tasks done culminated in the successful undertaking of two major mechanical tests which are fracture toughness and fatigue crack growth tests.

Even though the validation tests for the fracture toughness test failed to yield K_{IC} values, the values of K_Q obtained were valid for specimens with a thickness of 9 mm. In order for the validation test to be valid, the thickness of the specimen needs to be increased.

There are lots of improvements than can be implement to this project. For example, the material used in fabricating the accessories can be revised by using a better material or heat treatment so that the improve strength and stiffness can ensure better stability and accuracy of the tests performed. The dimensional tolerance also can be improved in order to get a better fit of the accessories.

5.2 RECOMMENDATIONS

5.2.1 Clevis Material and Heat Treatment

In this project, the clevis is made from low-cost Carbon Steel A760 which cannot be heat treated and having low toughness. Even though the material still can be used for this project, it is suggested the clevis is fabricated from heat-treatable AISI 4140 or AISI 4340.

5.2.2 Clevis Tolerance

Dimensional of the clevis also can be improved by reducing the tolerance applied. The clevis is not hold to the machine firmly due to the tolerance at the safety pin's hole. By reducing the tolerance, the clevis will hold to the machine firmly and improved the accuracy of the results obtained.

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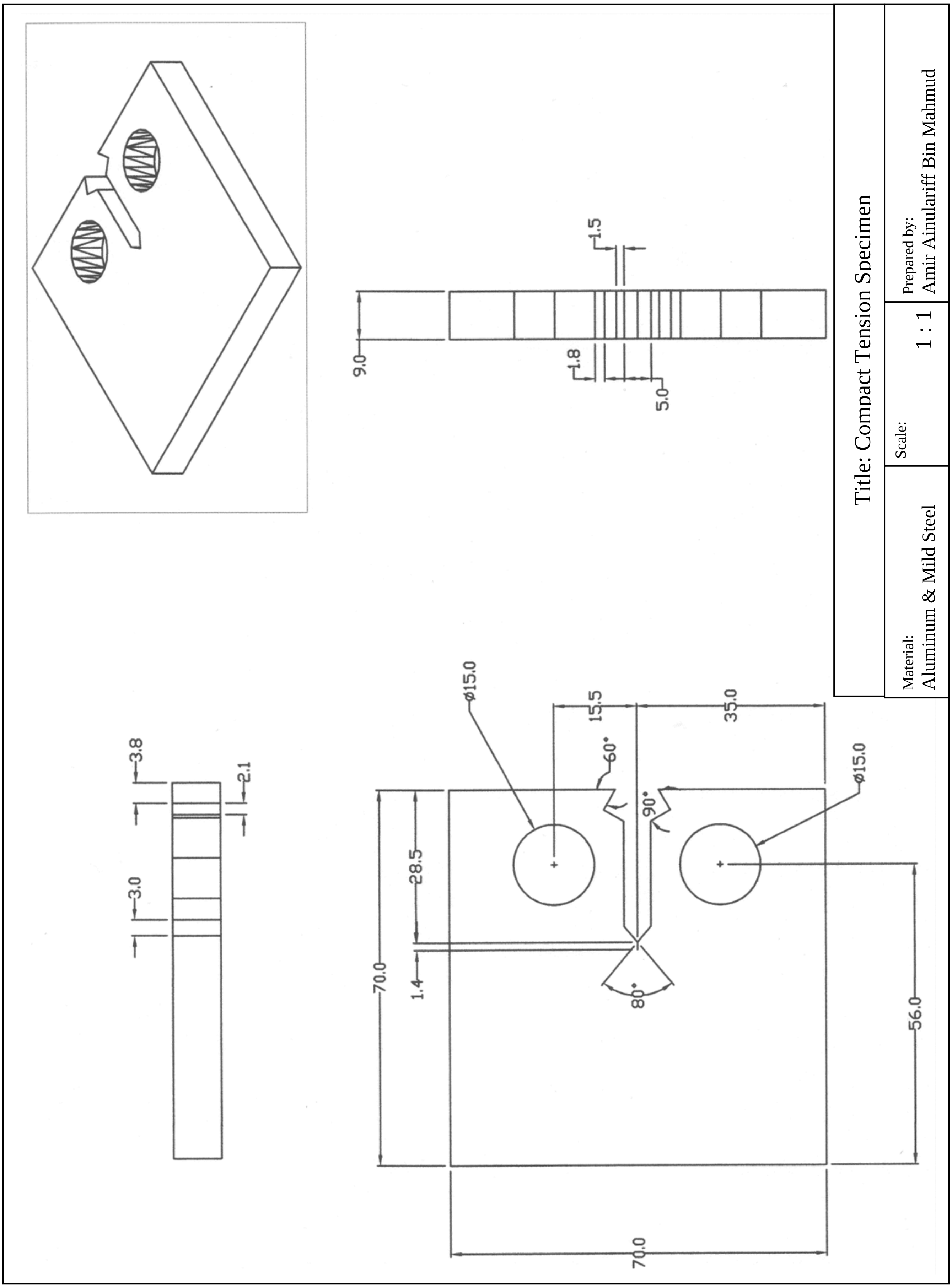
APPENDICES

Appendix 1: Design of the Test Specimen



Appendix 2: AMSLER Utility Testing Machine

Appendix 3: Suggested Standard Operating Procedure for General Procedure

UNIVERSITI TEKNOLOGI PETRONAS	STANDARD OPERATING PROCEDURE MATERIALS PROCESSING AND CHARACTERIZATION LABORATORY LABORATORY FACILITIES AND SERVICE UNIT MECHANICAL ENGINEERING

Machine : Universal Testing Machine (UTM 100kN)

Model Zwick Roell HA100

BEFORE OPERATION:

Make sure the machine is in good condition and SAFETY FIRST

CHANGING CLEVIS:

1. Clamp dummy to the gripper
2. Remove safety pin for the lower gripper
3. Lift the lower gripper upward using the pump
4. Remove lower gripper
5. Remove safety pin for the upper gripper
6. Remove upper gripper
7. Insert the lower clevis
8. Insert safety pin for lower clevis
9. Insert the upper clevis
10. Insert safety pin for upper clevis

CHANGING GAGE BEAM

1. Remove the normal gage from the extensometer
2. Screw the gage beam to the extensometer

Appendix 4: Suggested Standard Operating Procedure for Precrack Test

UNIVERSITI TEKNOLOGI PETRONAS	STANDARD OPERATING PROCEDURE MATERIALS PROCESSING AND CHARACTERIZATION LABORATORY LABORATORY FACILITIES AND SERVICE UNIT MECHANICAL ENGINEERING

Machine : Universal Testing Machine (UTM 100kN)

Model Zwick Roell HA100

OPERATIONAL INSTRUCTION:

1. Click TOOLKIT
2. Click DYNAMIC(CYCLE GENERATOR)
   2.1. Actuator : Actuator 1
   2.2. Control Mode : Load
   2.3. Wave Type : Sine
   2.4. No. Cycle : Depends
   2.5. Time Period : Depends
   2.6. Level A : P_{max}
   2.7. Level B : P_{min}
   2.8. Mean and Amplitude: Autofill
3. SEND and START at Cycle Generator
4. Varies Level A and B from lowest value to highest value. Immediately lower down the value of Level A and Level B after crack is initiated
5. To unload the specimen, set below values
   5.1. Cycle : 1
   5.2. Time Period : 1
   5.3. Level A : 0 kN
   5.4. Level B : 0 kN

Appendix 5: Suggested Standard Operating Procedure for Fracture Toughness Test

UNIVERSITI TEKNOLOGI PETRONAS	STANDARD OPERATING PROCEDURE MATERIALS PROCESSING AND CHARACTERIZATION LABORATORY LABORATORY FACILITIES AND SERVICE UNIT MECHANICAL ENGINEERING

Machine : Universal Testing Machine (UTM 100kN)

Model Zwick Roell HA100

OPERATIONAL INSTRUCTION:

1. Click TOOLKIT
2. Go to LOG DATA POINTS
   2.1. Change data name
   2.2. Select:
      - Load_CURRENT(kN) ACTUATOR 1
      - Ext._CURRENT(mm) ACTUATOR 1
   2.3. Click add
   2.4. Select AUTOMATIC, SYNS START/STOP, TIME INTERVAL to 000:00:01(depends) and FORMAT to excel
3. Go to SYSTEM CONFIGURATION
   3.1. Change OFFSET/GAINS setting:
      - EXT : zero channel
      - LOAD : zero channel
4. Click RAMP (DEFINE : RAMP 1)
   4.1. Actuator : Actuator 1
   4.2. Ramp : 1
   4.3. Control Mode : Stroke
   4.4. Rate : 0.01mm/s
5. Click SEND and START
6. Click STOP when load is approximately zero

Appendix 6: Suggested Standard Operating Procedure for Fatigue Crack Growth Test

UNIVERSITI TEKNOLOGI PETRONAS	STANDARD OPERATING PROCEDURE MATERIALS PROCESSING AND CHARACTERIZATION LABORATORY LABORATORY FACILITIES AND SERVICE UNIT MECHANICAL ENGINEERING

Machine : Universal Testing Machine (UTM 100kN)

Model Zwick Roell HA100

OPERATIONAL INSTRUCTION:

1. Click TOOLKIT
2. Go to LOG DATA POINTS
   2.1. Change data name
   2.2. Select:
      2.2.1. Load_CMAX(kN) ACTUATOR 1
      2.2.2. Load_CMIN(kN) ACTUATOR 1
      2.2.3. Load_CMEAN(kN) ACTUATOR 1
      2.2.4. Ext._CMAX(mm) ACTUATOR 1
      2.2.5. Ext._CMIN(mm) ACTUATOR 1
      2.2.6. Ext._CMEAN(mm) ACTUATOR 1
      2.2.7. Cycles Done ACTUATOR 1
   2.3. Click add
   2.4. Select AUTOMATIC, SYNS START/STOP, TIME INTERVAL to 000:00:01(depends) and FORMAT to excel
3. Go to SYSTEM CONFIGURATION
   3.1. Change OFFSET/GAINS setting:
      3.1.1. EXT : zero channel
      3.1.2. LOAD : zero channel

4. Click DYNAMIC(CYCLE GENERATOR)
    4.1. Actuator : Actuator 1
    4.2. Control Mode : Load
    4.3. Wave Type : Sine
    4.4. No. Cycle : Depends
    4.5. Time Period : Depends
    4.6. Level A : P_{max}
    4.7. Level B : P_{min}
    4.8. Mean and Amplitude: Autofill
5. SEND and START at Cycle Generator